RT NO. UMTA-MA-06-0099-80-1

IN-SERVICE PERFORMANCE AND COSTS OF METHODS TO CONTROL URBAN RAIL SYSTEM NOISE

Hugh J. Saurenman
Robert L. Shipley
George Paul Wilson

DECEMBER 1979
FINAL REPORT

DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
URBAN MASS TRANSPORTATION ADMINISTRATION
Office of Technology Development and Deployment
Office of Rail and Construction Technology
Washington DC 20590

Technical Report Documentation Page

1. Report No. UMTA-MA-06-0099-80-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IN-SERVICE PERFORMANCE AND COSTS OF METHODS TO CONTROL URBAN RAIL SYSTEM NOISE - FINAL REPORT		5. Report Date DECEMBER 1979 6. Performing Organization Code DTS-331
7. Author(s) Hugh J. Saurenman*, Robert L. Shipley**, George Paul Wilson*		8. Performing Organization Report No. DOT-TSC-UMTA-79-43
9. Performing Organization Name and Address Wilson, Ihrig & Associates* 5605 Ocean View Drive Oakland, CA 94618	DeLeuw, Cather & Company** 1201 Connecticut Ave., NW Washington, D.C. 20036	10. Work Unit No. (TRAIS) UM949/R9743 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U. S. Department of Transportation Urban Mass Transportation Administration Office of Technology Development and Deployment Office of Rail and Construction Technology Washington, D.C. 20590		13. Type of Report and Period Covered FINAL REPORT 14. Sponsoring Agency Code UTD-30
15. Supplementary Notes **Under contract to:	U. S. Department of Transportation Research and Special Programs Administration Transportation Systems Center Kendall Square, Cambridge, MA 02142	

16. Abstract
This is the final report of a study evaluating the acoustic and economic effectiveness of five methods of controlling wheel/rail noise and vibration on urban rail transit systems. Evaluations of rail grinding, wheel truing, resilient wheels, ring-damped wheels and welded vs. jointed rail were performed under revenue service conditions on the Market-Frankford Line of the Southeastern Pennsylvania Transportation Authority (SEPTA) rail transit system. This report summarizes the noise, vibration and cost results of the study and compares the measurement results with similar studies performed at other transit systems. Tests of the propulsion equipment noise showed that the propulsion equipment noise limited the reduction of wheel/rail noise that could be observed in this study. The general conclusions regarding noise and vibration control are: grinding rail without visible corrugations or other large scale roughnesses will result in only small reductions of noise and vibration; truing wheels without visible wheel flats or other large scale roughnesses will result in 0 to 5 dBA noise reduction and 0 to 10 dB reduction of ground vibration; resilient wheels are very effective at reducing wheel squeal but provide only small reductions of noise on tangent track; resilient wheels can provide significant reductions of ground vibration above 20 Hz; ring-damped wheels are very effective at reducing wheel squeal as long as the rings are free in the grooves; ring-damped wheels do not provide significant reductions of noise on tangent track; welded rail is to dB quieter than jointed rail. The economic evaluation was based upon SEPTA operations and costs incurred during the test program. This data was supplemented by information obtained from other North American transit systems and equipment and wheel manufactirers. Life-cycle cost equations were developed for the various control methods.

17. Key Words Wheel/Rail Noise, Resilient Wheels, Damped Wheels, Wheel Truing, Rail Grinding, Rail Noise, Rapid Transit Noise, Rail Transit Vibration, Ground-Borne Vibration and Noise	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	138	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

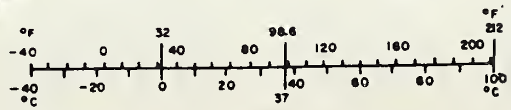
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This report is the final report of an extensive field evaluation of four methods of controlling rail rapid transit noise. The study has been performed by the DeLeuw, Cather Company (DCO) and Wilson, Ihrig & Associates (WIA) under contract to the U. S. Department of Transportation. The project is part of the Urban Rail Noise Abatement Program managed by the Transportation Systems Center (TSC), Cambridge, Massachusetts under the sponsorship of the Office of Rail and Construction Technology of the Urban Mass Transportation Administration, Office of Technology Development and Deployment.

A summary of the significant findings of the program is included with this report to provide an overview of the study program and the acoustical and economic conclusions of the study.

Significant contributions to the study were made by Robert L. Shipley, Michael C. Holowaty and Don Smith of DCP and by Hugh J. Saurenman, George Paul Wilson, Armin T. Wright, Stanley M. Rosen and Fred L. Palea of WIA. The project was technically monitored by Leonard Kurzweil and Robert Lotz of TSC.

The assistance of the Advisory Board of the American Public Transit Association (APTA) aided the development of information applicable to North American rail transit systems. Their participation in the program is gratefully acknowledged.

It is important to note that the measurement program required considerable assistance of SEPTA personnel. the co-operation of SEPTA, especially the assistance of Mr. Sandor Pali who was in charge of most aspects of the SEPTA participation and Mr. Harry Flemming who arranged the testing schedule to minimize the impact on revenue service, is sincerely appreciated.

The assistance of the Port Authority of New York and New Jersey personnel, under the supervision of Mr. Vincent J. Petrucelly, who performed the vibration measurement portion of the project, is also appreciated.

EXECUTIVE SUMMARY

The control of noise and vibration transmitted from rail rapid transit systems is a major concern for both new and existing transit systems. This study was designed to evaluate the reduction of wheel/rail noise that could be achieved on an existing transit system with rail grinding, wheel truing resilient wheels, damped wheels, and the use of welded vs. jointed rail. The noise reduction methods were tested under revenue operation conditions on the Market-Frankford Line of the Southeastern Pennsylvania Transit Authority (SEPTA) rapid transit system. In addition to the evaluation of the acoustic performance of the noise control methods, the study included a thorough economic analysis of the long and short term costs of the control methods if implemented on typical United States urban rail systems.

SEPTA trains with the special wheels and with standard solid steel wheels were tested on: welded and jointed track on an elevated structure with ballast and tie trackbed; jointed and welded track in a concrete invert subway; and at an at-grade short radius curve with ballast and tie trackbed. The evaluation thus included roar noise and impact noise on tangent track, and high frequency, high intensity wheel squeal noise as is commonly generated by trains traversing short radius curves such as a turnaround.

The primary components of the testing program were:

- o car interior noise on all test tracks,
- o wayside noise 7.5 m from track centerline at all except the subway test tracks,

- ground-borne vibration at the subway test track with welded rails,*
- rail and structure vibration at the elevated structure test track with welded rails,*
- damping loss factors of the resilient and damped wheels, and
- propulsion equipment noise.

The testing was performed between April 1976 and September 1978 using 2-car trains equipped with the special test wheels and standard solid steel wheels. Included in the test program was a one year wear period with the test trains and the test tracks in revenue service. The wear period was included so that the control methods could be evaluated immediately after installation and after the deterioration that results from use in normal revenue service.

Following is a summary of the results and major conclusions for each segment of the study.

Noise Control

On SEPTA, the control methods were observed to result in relatively small reductions of noise on both tangent and curved track with the notable exceptions that resilient and damped wheels very effectively reduced, and in some cases entirely eliminated, wheel squeal noise.

Measurements on SEPTA showed that the noise from the propulsion equipment limited the reduction of wheel/rail noise that could be observed in this study. The primary component of the propulsion equipment noise on the SEPTA cars is a pure tone at

---

*The vibration measurements were performed by personnel of the Port Authority of New York and New Jersey.

the blade passage frequency of the traction motor cooling fan. For evaluation of the tangent track acoustic data, the analysis procedure was modified to include a notch filter at the blade passage frequency of fan. This effectively removed the pure tone, increasing the separation between the wheel/rail noise and the propulsion equipment noise. However, the propulsion equipment noise was still found to limit the observable reduction of wheel/rail noise on tangent track to a maximum of 5 to 8 dBA.

Rail Grinding

In the SEPTA tests rail grinding was found to provide consistent but small noise reductions on tangent track and variable or non-reproducible results on curved track. A reduction of approximately 3 to 4 dBA was observed at the wayside after the first grinding of the jointed ballast and tie track; this reduction was apparently due to improved joint alignment. In general, the reductions for other test tracks and conditions were in the range of 0 to 2 dBA. Note that the SEPTA rail showed little evidence of corrugations and only limited shelling, spalling or pitting. These SEPTA results are similar to the results of rail grinding tests that have been performed on other transit systems that have relatively smooth rail.

Grinding of corrugated rail is known to be an effective method of eliminating the corrugation noise and thereby reducing the wheel/rail noise. Also, tests at several transit systems have shown reductions are achieved after grinding newly placed rail to remove the mill scale, rolling imperfections and rust. The conclusion is that grinding rail that does not have corrugations or other large scale roughness will not result in significant noise reductions.

Wheel Truing

The SEPTA tests showed measurable and fairly consistent reductions of noise on both tangent and curved track. An exception was a set of tests performed on tangent track immediately after truing wheels. Apparently because the cutter marks from the truing machine were still on the wheel running surface, the noise levels increased. This is similar to results obtained in Toronto and is not considered representative of the effectiveness of wheel truing after the wheels have been "run-in" by a few days of service.

The tests with trued wheels on tangent track showed that the wheels in new condition (with the surface smoothed with a lathe-type truing machine) were quieter by 0 to 2 dBA than the trued wheels (trued with the SEPTA under-floor milling machine type wheel truer). With the one exception noted above, the trued wheels on tangent track were consistently quieter than the worn wheels by 0 to 3 dBA.

The tests on the curved track before and after truing wheels showed a consistent 2 to 6 dB reduction resulting from truing the wheels. On the curved track the wheel squeal levels with the new and trued wheels were essentially equivalent.

Resilient Wheels

Only limited testing with the resilient wheels was possible because of problems experienced with these wheels. The SAB and Penn Bochum wheels were damaged due to overheating caused by problems with the brake systems and the Acousta Flex wheels were removed from service after a failure of the bond between the elastomer and the wheel rim. As a result, all of the resilient wheels were removed from the test program before they received a significant amount of wear.

The resilient wheels were found to be very effective at reducing wheel squeal; the Bochum wheels were most effective, the

Acousta Flex wheels were nearly as effective as the Bochum wheels, and the SAB wheels were considerably less effective than either the Bochum or Acousta Flex wheels. Although they were less effective, the SAB wheels did provide significant reductions of wheel squeal noise.

The reduction of noise with resilient wheels on tangent track was relatively small, ranging from 0 to 2 dBA.

Damped Wheels

Visco-elastic damped wheels were not installed on the SEPTA cars because of questions regarding their safety. However, an extensive series of tests was performed with ring-damped wheels.

The ring-damped wheels did not reduce noise on tangent track; however, they were very effective at reducing high frequency wheel squeal noise on curved track. Wheel squeal tests comparing the effectiveness of ring-dampers on the flange side and the field side of the wheel were inconclusive and did not indicate which side was most effective at reducing wheel squeal. From a wheel life standpoint, flange side grooves provide a large advantage over field side grooves in that placing grooves on the field side reduces the effective wheel tread thickness and thereby reduces wheel life on SEPTA, field side grooves reduce wheel life approximately 25%. Flange side groove do not decrease wheel life.

The damping rings were found to be rigidly frozen in the grooves after ten months of revenue service at SEPTA. The tests with the rings frozen in the grooves showed that the rings were no longer effective dampers and that they did not provide significant control of wheel squeal noise. The cause of the bonding of the rings to the grooves was most likely a combination of corrosion and brake dust. A chemical analysis of loose particles taken from the grooves after removal of the rings found the particles to be basically composed of iron. Further research on the mechanism causing the bonding and prevention of the bonding is required before ring-dampers can be recommended for use on transit car fleets. After

the frozen rings were removed and new rings inserted, the wheel squeal was again significantly reduced. Note that the London Transport System, which has had ring damped wheels in service since 1938, has not reported any problems with the ring-dampers bonding to the grooves. Also, CTA has had ring-dampers installed on several new 2400 series cars for several years without the rings freezing in the grooves.

Welded vs. Jointed Rails

The acoustical advantages of changing from jointed rails to welded rails have long been recognized. The testing of this study allows evaluation of the noise reduction achieved with welded rail in subway and on ballasted elevated structure at the SEPTA facilities.

On the elevated structure the noise levels for welded track compared to jointed track averaged 4 dBA lower at the wayside and 2 dBA lower inside the cars. The difference inside the cars was even less on the subway test tracks, ranging from 0 to 2 dBA.

Vibration Control

As an adjunct to the acoustic measurements, measurements were also performed of rail, structure and ground-borne vibration at the welded test sections in the subway and on the elevated structure. The measurements included trains with worn and trued solid steel wheels and the three sets of resilient wheels. Tests were performed before and after rail grinding.

The results of the vibration tests and the results of tests at other systems indicate that the use of resilient wheels results in substantial reductions of ground-borne noise and vibration above 20 Hz. The results with trued solid steel wheels indicate that substantial reductions can also be achieved with wheel truing. The amount of reduction is, of course, dependent on the wheel condition before truing; for example, it has long been known that removing wheel flats and other major defects on worn wheels is an important first step in controlling ground-borne noise and vibration.

As with airborne noise the SEPTA test results indicate that grinding rail that does not have major irregularities due to corrugation, pitting, spalling or shelling does not result in a significant reduction of ground-borne noise and vibration.

Economic Analysis

Parallel to the performance of the acoustic testing, information was collected on the cost of the noise control methods (with the exception of welded rail) and other factors that relate to the implementation of the methods. The primary source of data on the total cost (initial, operating and maintenance) for each of the noise control methods was observation and analysis of SEPTA operations and costs during the test phase of the program.

To supplement the data available from SEPTA, an extensive survey of other North American transit systems was carried out. The purpose of the program was to determine specific experiences of the transit systems with the noise control methods; including information such as labor, time, costs, and operational experience associated with rail grinding, wheel truing and resilient wheels. As most transit systems presently have wheel truing and rail grinding equipment, a major purpose of the survey was to collect information on the existing programs. Typical information collected included types of equipment, criteria for deciding when to grind rail and true wheels, labor requirements and cost of equipment.

The survey of transit systems was divided into two parts - first a preliminary survey to collect information on the equipment used by the transit systems and second an indepth questionnaire to determine the cost breakdowns for labor and equipment for rail grinding and wheel truing. To supplement the information about the experience of the transit systems with the noise control methods, the survey gathered information about each system's operations, the equipment operated and the physical layout of the system.

Information was also obtained from equipment and wheel manufacturers concerning the purchase costs, maintenance costs, and projected service lives for wheel truing and rail grinding equipment and for resilient, solid steel, and ring-damped wheels.

The data is published in Report No. UMTA-MA-06-0025-78-7, In-Service Performance and Costs of Methods to Control Urban Rail System Noise, Initial Test Series Report.

Life-cycle cost equations were developed for resilient wheels, steel wheels, ring-damped wheels, wheel truing, and rail grinding. These equations calculate the present value of the life-cycle costs for each element and consider initial costs, maintenance costs, operations costs, and projected service lives. Sensitivity analyses were performed to determine the effect of variable data on the results produced by the equations. The life-cycle equations can be used to calculate the present value of costs for employing each of the noise abatement techniques on any rapid transit system.

- Wheels:
  a. The life-cycle cost analysis showed that a car set of resilient wheels will cost between 1.2 and 1.6 times the cost of a car set of solid steel wheels over the life span of the resilient wheels, assuming that the wear rate for the resilient and solid steel wheels is the same. A car set of ring-damped wheels having grooves on the field side of the wheels will cost approximately 1.4 times the cost of a car set of solid steel wheels over the life span of the solid steel wheels. This is due to the decrease in wheel life (25%$\pm$) caused by the reduction in tread thickness due to the groove. Ring-damped wheels with grooves on the flanged side of the wheels will cost approximately 1.05 times the cost of the solid steel wheels.

b. The life cycle cost is not sensitive to maintenance and inspection costs but is dependent upon initial costs and length of service life. One manufacturer claims that resilient wheels wear at a 40 percent slower rate than solid steel wheels. If correct, this increased life would have a marked effect on the present value of the life-cycle costs reducing the life-cycle costs by 25%±.

c. It had been planned that the service life of the resilient wheels would be determined during the field testing program. Unfortunately, all resilient wheels were removed from services prior to a sufficient amount of mileage being accrued by the wheels to allow significant wear measurements to be made.

- Wheel Truing:

1. The cost of wheel truing varies greatly depending upon the type of equipment used in the wheel truing process. Wheel truing one car set of wheels on SEPTA's Broad Street Line, performed on an above floor lathe, requires 80 man hours of effort at a cost of $775 (1977$); whereas, wheel truing one car-set of wheels on the Market Frankford Line, performed on an underfloor milling machine, requires only 8.5 man hours of effort at a cost of $85 (1977$). The purchase price of above floor and underfloor equipment is similar, however.

2. The large difference in cost for wheel truing is also found on the other transit properties and points out the great advantage of the underfloor method of wheel truing.

3. Wheel truing is not a cost-effective method of achieving noise reduction except in cases where large wheel flats have occurred.

- Rail Grinding:

  SEPTA is one of five North American transit properties owning a rail grinding train. Four systems do not utilize rail grinding. The Port Authority Transit Corporation (PATCO) contracts for rail grinding services on a bi-annual basis. The systems owning rail-grinding equipment are those which have a high incidence of rail corrugations. Rail grinding is not a cost-effective method of achieving noise reduction except in instances where rail corrugations are a significant problem.

CONTENTS

SECTION	PAGE
1. INTRODUCTION	1-1
1.1 Noise Control Methods	1-3
1.1.1 Resilient Wheels	1-3
1.1.2 Damped Wheels	1-8
1.1.3 Wheel Truing	1-12
1.1.4 Rail Grinding	1-12
1.1.5 Rail Welding	1-14
1.2 Test Program	1-14
1.3 Economic Analysis	1-16
2. TEST PROGRAM	2-1
2.1 Test Tracks	2-4
2.2 Wayside and Car Interior Noise Tests	2-6
2.3 Propulsion Equipment Noise Tests	2-9
2.4 Ground-Borne Vibration Tests	2-10
2.5 Wheel Vibration Decay Rate	2-11
2.6 Wheel and Rail Roughness	2-11
3. PROPULSION EQUIPMENT NOISE TEST RESULTS	3-1
4. ACOUSTICAL RESULTS	4-1
4.1 Introduction	4-1
4.2 Overview of Measurement Results	4-2
4.3 Rail Grinding	4-11
4.3.1 SEPTA Results	4-11
4.3.2 Generalized Rail Grinding Results	4-14

CONTENTS (CONT'D)

SECTION	PAGE
4.4 Wheel Truing..................................	4-16
4.4.1 SEPTA REsults............................	4-16
4.4.2 Generalized Wheel Truing Results.........	4-18
4.5 Resilient Wheels..............................	4-18
4.6 Damped Wheels.................................	4-22
4.7 Jointed Vs. Welded Rails......................	4-26
5. GROUND-BORNE VIBRATION..........................	5-1
5.1 Comparison of Vibration Levels................	5-3
5.2 Vibration Reduction with Resilient Wheels.....	5-8
5.3 Vibration Reduction with Wheel Truing.........	5-10
6. ECONOMIC ANALYSIS...............................	6-1
6.1 Surveys of Transit Systems and Manufacturers...	6-1
6.2 Cost Analysis.................................	6-2
6.2.1 Wheels.....................................	6-2
6.2.2 Wheel Truing...............................	6-6
6.2.3 Rail Grinding..............................	6-7
7. REFERENCES......................................	7-1
APPENDIX A: GRAPHS OF AVERAGE SOUND LEVELS AND TABULATIONS OF MEASURED NOISE REDUCTIONS....	A-1
APPENDIX B: REPORT OF NEW TECHNOLOGY...................	B-1

ILLUSTRATIONS

FIGURE		PAGE
1-1a	Photographs of Resilient Wheels................	1-4
1-1b	Cross-Sections of Resilient Wheels............	1-5
1-2a	Photograph of Ring-Damped Wheel................	1-9
1-2b&c	Cross-Section of Ring-Damped Wheels...........	1-10
1-3	SEPTA Underfloor Milling Machine Type Wheel Truer....................................	1-13
1-4	Example of Wheel After Truing on SEPTA Wheel Truer....................................	1-13
1-5	SPENO Rail Grinder............................	1-15
3-1	Wayside Noise Level for Propulsion Equipment as a Function of Speed - 7.5 Meters from Track Centerline...............................	3-3
3-2	Levels of Propulsion Equipment Noise as a Function of Speed - Car Interior...............	3-4
4-1	Wayside Sound Levels at TW Test Track with New and Worn Wheels and with Worn and Ground Rail - Test Series 2...................................	4-5
4-2	Wayside Sound Levels at TW Test Track - Test Series 1...................................	4-6
4-3	Car Interior Sound Levels on TW Test Track with New and Worn Wheels and with Worn and Ground Rails - Test Series 2..................	4-7
4-4	Wayside Sound Level at TJ Test Track - Test Series 1......................................	4-8
4-5	Wayside Sound Levels at TJ Test Track - Test Series 2......................................	4-9
4-6	Car Interior Sound Levels on the Tangent Jointed Test Track with New and Worn Wheels and with Rails Worn 1 and 2 Years - Test Series 2......................................	4-10

FIGURE		PAGE
4-7	Comparison of Wayside Levels on Tangent Jointed and Welded Rails, B & T Trackbed........	4-28
4-8	Comparison of Car Interior Levels on Jointed and Welded Rails, Subway Test Tracks............	4-29
5-1	Invert Vertical Vibration at Four Transit Systems - All Tests were on Tangent Welded Rails with Standard Steel Wheels................	5-4
5-2	Average Vertical Vibration Spectra at Invert - Subway Test Track, Tangent Welded Rails.........	5-5
5-3	Average Vertical Vibration Spectra at Basement Location - Subway Test Track, Tangent Welded Rail..	5-6
5-4	Vertical Vibration Spectra for Resilient Wheels Relative to Standard Wheels - Tangent Welded Rails......................................	5-9
5-5	Average Vibration Spectra for New Resilient Wheels and Trued Standard Wheels Relative to Worn Standard Wheels - Subway Test Track, Ground Welded Rails..............................	5-11
5-6	Average Vibration Spectra for New Resilient and Trued Standard Wheels Relative to Worn Standard Wheels - TW Test Track, Ground Rails...	5-12
5-7	Spectra of Vertical Vibration Levels after Rail Grinding Compared to Before Rail Grinding - Tangent Welded Rail in Subway...................	5-14
A-1	Average Wayside Noise Levels at TW Test Track During Series 1 and 2 for Various Wheels and Rail Conditions..................................	A-4

ILLUSTRATIONS (CONT'D)

FIGURE		PAGE
A-2	Average Car Interior Noise Levels at TW Test Track During Series 1 and 2 for Various Wheels and Rail Conditions	A-5
A-3	Average Wayside Noise Levels at TJ Test Track During Series 1 and 2 for Various Wheels and Rail Conditions	A-6
A-4	Average Car Interior Noise Levels at TJ Test Track During Series 1 and 2 for Various Wheels and Rail Conditions	A-7
A-5	Average Car Interior Noise Levels at Subway Test Tracks During Series 1 and 2 for Various Wheels and Rail Conditions	A-8
A-6	Average Wayside Noise Levels at TURN Test Track During Series 1 and 2 for Various Wheels and Rail Configurations	A-9
A-7	Average Car Interior Noise Levels at TURN Test Track During Series 1 and 2 for Various Wheels and Rail Conditions	A-10

TABLES

TABLE		PAGE
2-1	SUMMARY OF TEST PROGRAM........................	2-2
4-1	SUMMARY OF RAIL GRINDING RESULTS. THE RESULTS FROM VARIOUS TESTS AT SEVERAL TRANSIT SYSTEMS ARE GIVEN SHOWING THE LEVELS WITH GROUND RAIL RELATIVE TO WORN OR NEW RAIL....................	4-15
4-2	SUMMARY OF WHEEL TRUING RESULT. THE RESULTS SHOWN ARE THE LEVELS WITH WHEELS IN A "TEST CONDITION" RELATIVE TO WHEELS IN A "REFERENCE CONDITION"......................................	4-19
4-3	SUMMARY OF EFFECTIVENESS OF RESILIENT WHEELS. THE TABLE SHOWS THE LEVELS WITH RESILIENT WHEELS RELATIVE TO LEVELS WITH SMOOTH STANDARD WHEELS..	4-20
4-4	SUMMARY OF EFFECTIVENESS OF DAMPED WHEELS. THE TABLE SHOWS THE LEVELS WITH DAMPED WHEELS RELATIVE TO LEVELS WITH SMOOTH STANDARD WHEELS..	4-24
A-1	CHANGE IN NOISE LEVEL AFTER RAIL GRINDING ON TW TEST TRACK. FOR EACH WHEEL TYPE THE TABLE SHOWS LEVELS WITH GROUND RAILS AND RAILS WORN 24 MONTHS RELATIVE TO LEVELS WITH RAILS WORN BY 12 MONTHS OF NORMAL REVENUE SERVICE..........	A-11
A-2	CHANGE IN NOISE LEVEL AFTER RAIL GRINDING ON TJ TEST TRACK. FOR EACH WHEEL TYPE THE TABLE SHOWS THE LEVEL WITH GROUND RAILS AND RAILS WORN 24 MONTHS RELATIVE TO RAIL WORN BY 12 MONTHS OF NORMAL REVENUE SERVICE............	A-12
A-3	CHANGE IN CAR INTERIOR NOISE LEVEL AFTER RAIL GRINDING SUBWAY TEST TRACKS. THE TABLE SHOWS THE LEVELS WITH GROUND RAILS RELATIVE TO LEVELS WITH RAIL WORN BY 12 MONTHS OF NORMAL REVENUE SERVICE................................	A-13

TABLE		PAGE
A-4	CHANGE IN WHEEL SQUEAL NOISE LEVELS AFTER GRINDING TURN TEST TRACK. THE TABLE SHOWS, FOR EACH COMBINATION OF WHEEL TYPE, THE AVERAGE LEVELS WITH GROUND RAILS RELATIVE TO THE AVERAGE LEVELS FOR THE TEST SERIES 2 WORN RAILS. THE GROUND RAIL RESULTS FROM TEST SERIES 1 AND TEST SERIES 2 HAVE BEEN COMBINED FOR THIS TABLE	A-14
A-5	EFFECTIVENESS OF WHEEL TRUING AT REDUCING NOISE FOR TW TEST TRACK. THE NOISE LEVELS FOR STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO STANDARD WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED	A-15
A-6	EFFECTIVENESS OF WHEEL TRUING AT REDUCING NOISE FOR TJ TEST TRACK. THE NOISE LEVELS FOR STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO STANDARD WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED	A-16
A-7	EFFECTIVENESS OF WHEEL TRUING AT REDUCING CAR INTERIOR NOISE FOR SUBWAY TEST TRACKS. THE LEVELS FOR STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO STANDARD WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED	A-17
A-8	EFFECTIVENESS OF WHEEL TRUING AT REDUCING WHEEL SQUEAL. THE LEVELS WITH STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED. THE RESULTS OF TEST SERIES 1 AND TEST SERIES 2 HAVE BEEN COMBINED TO DERIVE THIS TABLE	A-18
A-9	EFFECTIVENESS OF RESILIENT WHEELS AT REDUCING NOISE. THE TABLE SHOWS THE LEVELS WITH RESILIENT WHEELS RELATIVE TO LEVELS WITH TRUED STANDARD STEEL WHEELS FOR THE SEPTA TESTS.	A-19

TABLE		PAGE
A-10	REDUCTION OF SOUND LEVELS WITH RING-DAMPED WHEELS ON TANGENT TRACK. OVERALL SOUND LEVELS WITH RINGS IN RELATIVE TO RINGS OUT. ALL TESTS WERE WITH GROOVED #1 TRAIN......	A-20
A-11	AVERAGE EFFECTIVENESS OF RING-DAMPED WHEELS AT REDUCING WHEEL SQUEAL. OVERALL SOUND LEVELS WITH RINGS IN RELATIVE TO OVERALL SOUND LEVELS WITH RINGS OUT.....................	A-21

1. INTRODUCTION

This document is the final report on a field measurement and cost study project intended to evaluate the applicability of five methods of controlling wheel/rail noise on urban rail transit systems. The study is part of the Urban Rail Noise Abatement Program through which the Urban Mass Transportation Administration (UMTA) is sponsoring research projects to develop the technology for predictable control of noise and vibration on urban rail systems. The U. S. Department of Transportation, Transportation Systems Center, is the systems manager for the program.

Noise created by the operations of urban rapid transit systems is a source of intrusion and discomfort for both the transit system patrons and the adjacent communities. There are many potential sources of noise from transit system facilities and equipment; however, the most significant source is clearly the operation of the transit trains. There are two primary sources of noise from transit trains: the noise from the propulsion equipment and the noise created by steel wheels rolling on steel rails, referred to as wheel/rail noise. On many older transit systems, the wheel/rail noise is predominant; however, with continuous welded rail the wheel/rail noise and propulsion equipment noise are of similar magnitude at normal operating speeds. Wheel/rail noise is considered to be created by three general mechanisms: squeal noise which is typically excited when trains are on short-radius curves; impact noise caused by discontinuities such as rail joints and wheel flats; and roar noise which is the residual noise of wheels rolling on rails in the absence of wheel squeal or significant impact noise.

Five methods of controlling wheel/rail noise have been investigated in this study: rail grinding, wheel truing,

the use of resilient wheels, the use of damped wheels and the use of welded vs. joint rail. The methods have all been tested under actual revenue service conditions on the Southeastern Pennsylvania Transportation Authority (SEPTA) Market-Frankford Line. The ultimate goal of the research reported herein is to provide information that can be used to evaluate the effectiveness of these wheel/rail noise control methods on existing and future transit systems and to determine the mix of available wheel/rail noise control methods that will result in the greatest overall benefit. Included in this evaluation is the reduction of noise radiated to adjacent communities and the reduction of patron noise exposure. This project was designed to provide information on both the long-term and short-term costs and acoustical effectiveness of the various noise abatement procedures if they were implemented on typical urban rail systems in the United States.

Four previous interim reports have been prepared for this study. The first two reports presented the Experimental Design[1*] and Test Plan[2] for the study; the third interim report[3] presented the results of the first three sets of acoustical tests, the preliminary analysis of the cost data, and a summary of the survey of transit systems and manufacturers of noise control equipment; and the fourth interim report[4] presented the results of the final four sets of acoustical tests. The detailed results of all of the testing as well as detailed description of the test locations, procedures and equipment are presented in the interim reports. As a result, only brief summary discussions of this material are given in this report.

---

*References are listed at the end of the report.

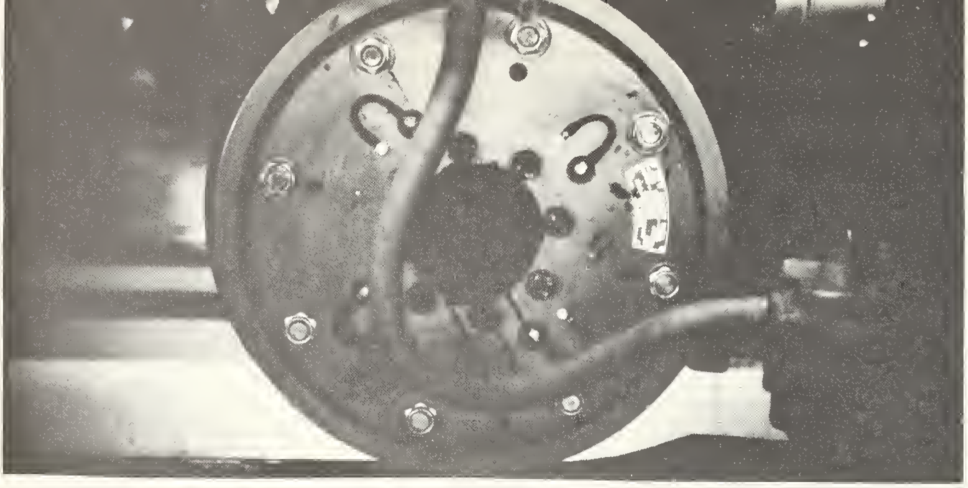
The purpose of this report is to present the generalized acoustical and economic results of this study, to compare noise control results of this study with representative results demonstrated by other similar studies and, finally, to draw some generalized conclusions regarding the results, acoustical and economic, that can be expected when the five noise control methods studied are applied to North American rapid transit systems. A summary of the overall results of this study is given in the Executive Summary Section.

1.1 NOISE CONTROL METHODS

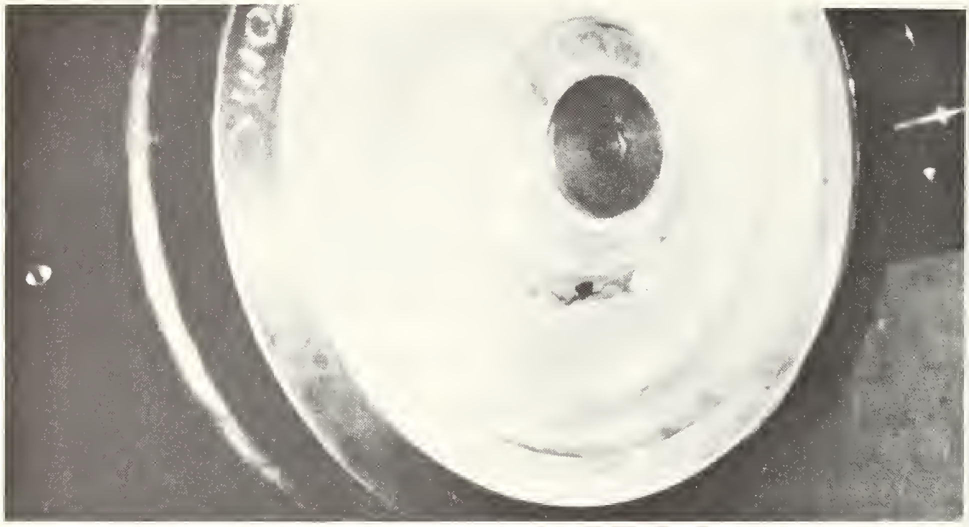
1.1.1 Resilient Wheels

Three sets of resilient wheels were included in the study. The resilient wheel designs all include resilient material separating the hub and tire. The resilient material increases the damping of the wheels which reduces the resonant noise radiation. In addition, the resilient material acts as a vibration isolation system that can reduce the dynamic forces applied to the rail and can reduce the vibration transmitted from the wheel/rail interface back through the wheels to the truck and the car body.

The three types of resilient wheels are shown in Figures 1-la & b. Figure 1-la presents photographs of the test wheels and Figure 1-lb shows cross-sections of the resilient wheels indicating the location of the elastomeric material between the wheel hub and the tire. The Acousta Flex wheels essentially consist of a steel rim and aluminum hub that are threaded together. Elastomeric material is injected into the thread space and bonded to the rim and the hub. The Penn Bochum wheels have small elastomer blocks between the rim and hub of the wheels. The SAB wheels have the most complex design of the resilient wheels tested, the vibration isolation and the damping being provided by elastomer discs in shear.



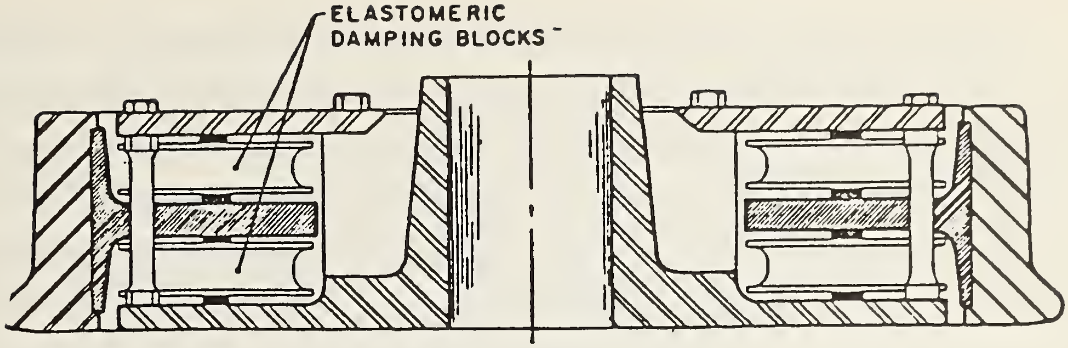
SAB RESILIENT
WHEEL



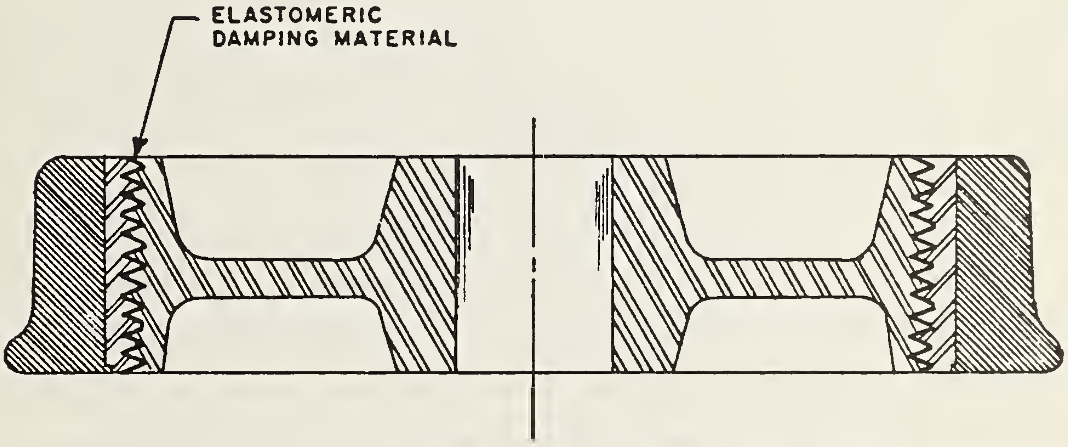
ACOUSTA FLEX
RESILIENT WHEEL

PENN CUSHION (BOCHUM)
RESILIENT WHEEL

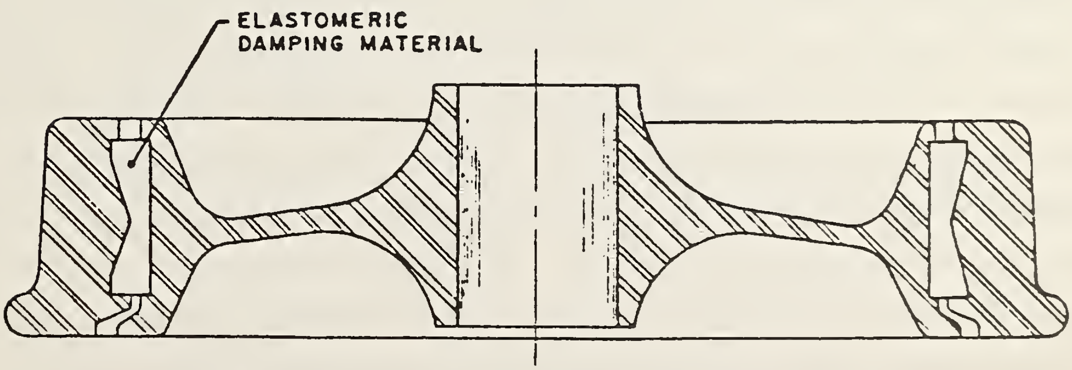
FIGURE 1-1a. PHOTOGRAPHS OF RESILIENT WHEELS



SAB RESILIENT WHEEL



ACOUSTA FLEX RESILIENT WHEEL



PENN CUSHION (BOCHUM) RESILIENT WHEEL

FIGURE 1-1b. CROSS-SECTIONS OF RESILIENT WHEELS

As described in the Second Test Series Report[4] , tests of the resilient wheels showed that they all have much higher internal damping than the standard steel wheels. The Acousta Flex and Penn Bochum wheels had essentially the same damping and the SAB wheels had damping factors six to ten times lower than the other resilient wheels. However, since the SAB wheels have approximately 10 mm static deflection compared to less than 1 mm for both the Acousta Flex and Bochum wheels, the SAB wheels provide significantly more vibration isolation than the other resilient wheels. As discussed later, the lower damping of the SAB wheels results in higher squeal levels on curved track while the greater vibration isolation results in lower ground vibration in some frequency ranges.

The test schedule included testing of the resilient wheels in new, worn and trued condition. However, problems were experienced with all three types of resilient wheels which resulted in the wheels being removed from the test program before they had received significant wear. The Acousta Flex wheels were removed from the program after a bonding failure occurred between the rim and the elastomeric material, apparently due to incomplete bonding during manufacturing. One set of the Penn Bochum wheels experienced damage to the rubber blocks after a dynamic brake failure required the exclusive use of the mechanical, tread brake system. Initial imperfections of two blocks, not detected by the manufacturer's quality control system, were increased due to the combination of the resulting high wheel temperatures and the in-service compression stresses. The SAB wheels were removed from the program after the wheels on one axle suffered severe damage from overheating caused by application of the hand brake during revenue service.

The problems with the resilient wheels were all discovered before any structural failure of the wheels. There is no indication that there was any threat to the safety of the patrons or any threat of damage to SEPTA facilities. However, the fact that the damage to the Penn Bochum and SAB wheels was related to overheating caused by the tread braking system raises serious questions regarding the applicability of resilient wheels to heavy rail transit systems with tread brakes. Since failure of the dynamic braking system is not uncommon on the SEPTA cars, use of resilient wheels on this system is clearly inappropriate. However, there are numerous examples of successful application of resilient wheels to transit cars. Two examples of successful application of resilient wheels to tread brake systems are the use of resilient wheels on PPC streetcars and a test program with resilient wheels performed by London Transport. Most of the original PPC cars, all of which had tread braking systems, were equipped with resilient wheels. Although many of the PPC cars remaining in service are now equipped with solid steel wheels, the resilient wheels were widely used for many years and are still in use.

The London Transport tests[5] included use of SAB and Bochum wheels for several years of revenue service. The SAB wheels were run 367,000 km (228,000 miles) on transit cars with tread brakes. Of the total mileage, 53,000 km (33,000 miles) was on a car with no dynamic braking; however, no problems related to the frictional heat were observed. The Bochum wheels were operated for 212,000 km (132,000 miles) of revenue service with no problems related to the heat from brake friction observed.

The experience of other transit systems with resilient wheels indicate that with an increase in the reliability of the

dynamic braking system, resilient wheels could be considered for even the SEPTA system.

1.1.2 Damped Wheels

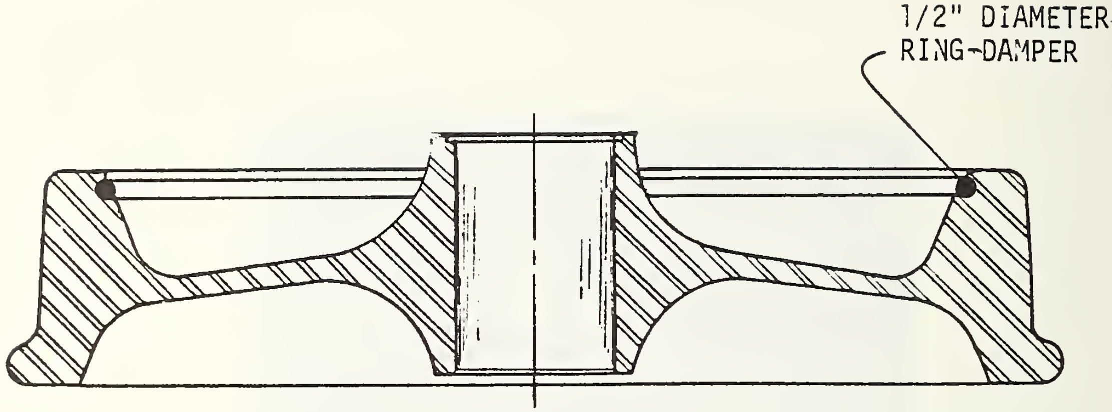
Damped wheels are conventional steel wheels that have been treated to increase the damping of mechanical vibration. The increased damping reduces the resonant vibration of the wheels. This results in lower levels of wheel squeal and can also result in lower levels of road and impact noise radiated by the wheels.

The test program was to have included the testing of a 2-car set of visco-elastic damped wheels. Upon receiving the dampers, SEPTA decided not to allow them to be placed in service as there was doubt concerning the ability of the dampers to remain in place under operating conditions. Subsequently, the testing of the visco-elastic damped wheels was dropped from the program.

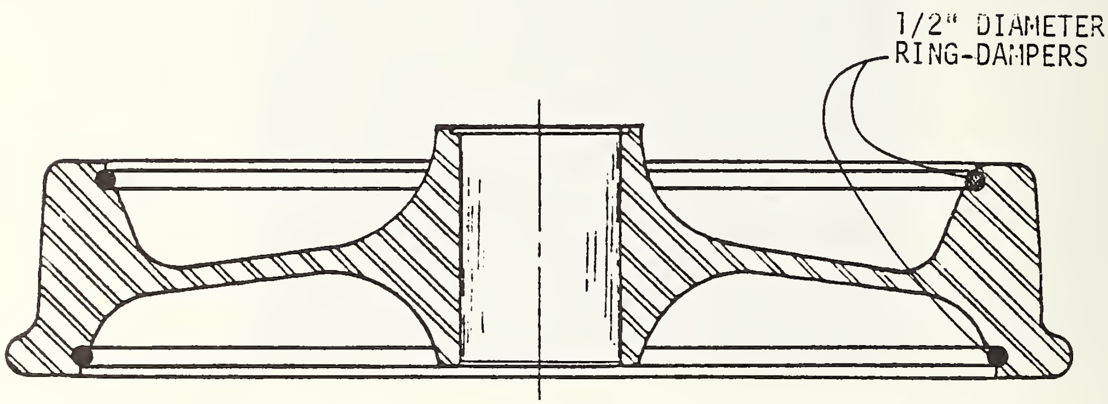
In the second series of acoustical tests, ring-damped wheels were added to the program. Figures 1-2a, b & c presents a photograph of a ring-damped wheel with the ring installed and illustrates the cross-sections of the two types of ring-damped wheels. As shown in the Figures the ring-damped wheels consist of a mild steel ring inserted in a groove cut into the inside diameter of the wheel tread. The damping results from the friction between the wheel and the ring.

The tests of the damping loss factors presented in the Second Test Series Report[4] showed that the ring-dampers provided significant damping above about 1400 Hz. The damping factors for the ring-damped wheels above 1400 Hz were approximately equal to those of the SAB wheels. The rings did not supply any damping below 1400 Hz. The ring dampers appear to be a cost-effective method of providing high frequency damping. Unfortunately,

FIGURE 1-2a. PHOTOGRAPH OF RING-DAMPED WHEEL



b. RING-DAMPER ON FIELD SIDE



c. RING-DAMPERS ON FIELD AND FLANGE SIDES

FIGURE 1-2b & c. CROSS-SECTION OF RING-DAMPED WHEELS

the acoustical tests indicate that after several months of service the rings can "freeze" in the grooves due to corrosion and/or foreign material such as brake dust, causing a bond to form between the ring and wheel groove. When frozen in the grooves, the rings do not provide sufficient damping to control wheel squeal.

Ring-dampers have been tested and implemented by other transit systems without having the rings lock in the grooves. Ring-dampers installed on several of the CTA 2400 series cars were observed to be free in the grooves even after approximately one year of revenue service. Clearly the mechanism causing the rings to freeze in the grooves needs further investigation. Possibly the problem could be avoided by constructing the rings of corrosion resistant material such as stainless steel. However, if the freezing of the rings in the grooves results from foreign material such as brake dust, use of corrosion resistant material may not solve the problem; a coating of some kind may be required to keep foreign material out of the ring groove.

As shown in Figures 1-2b & c, the groove for the ring-dampers can be cut in either side of the tread. Most of the testing was performed with a 2-car set of wheels grooved on the field side as shown in Figure 1-2b. An extra test series was performed with a 1-car train grooved for ring-dampers on the both sides as shown in Figure 1-2c. The purpose of these tests was to compare the effectiveness of ring-dampers on the field side and the flange side at reducing wheel squeal.

By placing ring-dampers on the flange side, the groove is placed in a location where the useful life of the tire is not affected. Cutting the groove on the field side requires removing material from the wheel tire and reduces the useful life of the wheel.

1.1.3 Wheel Truing

Wheel truing consists of grinding or machining the wheel tire running surfaces to a desired degree of smoothness removing any non-uniformities and reducing the roughness of the running surface. There are several types of wheel truers in use on North American transit systems. All of the transit systems have some procedure that is used for truing wheels. SEPTA has an underfloor wheel truer that uses milling machine type cutters. Using this machine, the wheels of a car can be trued without removing the trucks from the car.

Figure 1-3 is a picture of the SEPTA wheel truer and Figure 1-4 is a photograph of a wheel that has just been trued with this machine. The pattern of the cutter is clearly identifiable on the wheel surface; this pattern disappears after several weeks of service.

Another fairly common type of wheel truing process utilizes a large lathe. The lathe type wheel truers result in a smoother running surface but require significantly more effort to true each wheel since the axles must be removed from the trucks.

The test program at SEPTA included standard steel wheels that were new, trued and in worn condition. New wheels that are delivered to SEPTA have had the wheel surface smoothed with a lathe type wheel truer. Hence, the test program was designed to evaluate both methods of wheel truing.

1.1.4 Rail Grinding

The effectiveness of rail grinding at reducing noise has been evaluated by performing a number of tests before and after rail grinding. When feasible, the test tracks included a

FIGURE 1-3. SEPTA UNDERFLOOR MILLING MACHINE TYPE WHEEL TRUER

FIGURE 1-4. EXAMPLE OF WHEEL AFTER TRUING ON SEPTA WHEEL TRUER

segment of a "control" track which was not ground throughout the test program. This allowed simultaneous measurements of worn and ground rail reducing the influence of uncontrollable factors such as weather conditions or changes in equipment characteristics on the observed reduction due to rail grinding.

The rail grinding at SEPTA is performed with a SPENO grinding train as shown in Figure 1-5. The grinding train consists of a power car and four grinding buggies having a total of 24 abrasive grinding wheels. Each grinding wheel is independently adjustable to give a smooth rail head contour.

1.1.5 Rail Welding

The SEPTA system contains both jointed and welded rail, generally composed of 100 lb./yd. section. Jointed rail is connected by 4-hole joint bars. All welded rail is field welded using the Thermite process.

1.2 TEST PROGRAM

The testing for this study was carried out between April 1976 and September 1978 using mostly 2-car trains equipped with the special test wheels and standard steel wheels. The test program primarily consisted of measurements of wayside noise 7.5 m (24.6 ft.) from the track centerline and measurement of car interior noise. The car interior noise was measured at the center of a car and over the truck at the train center. At the tangent test tracks, tests were made at three nominal speeds; 40, 60 and 80 km/hr (27, 41, and 55 mph). The actual speed during each test was recorded with a portable speedometer. Tests in stations and at a short radius curve were made at normal operating speed only.

To supplement the acoustical measurement data and to provide more information on the characteristics of transit car noise generation and the effects of application of the noise reduction procedure, measurements of the following were also performed:

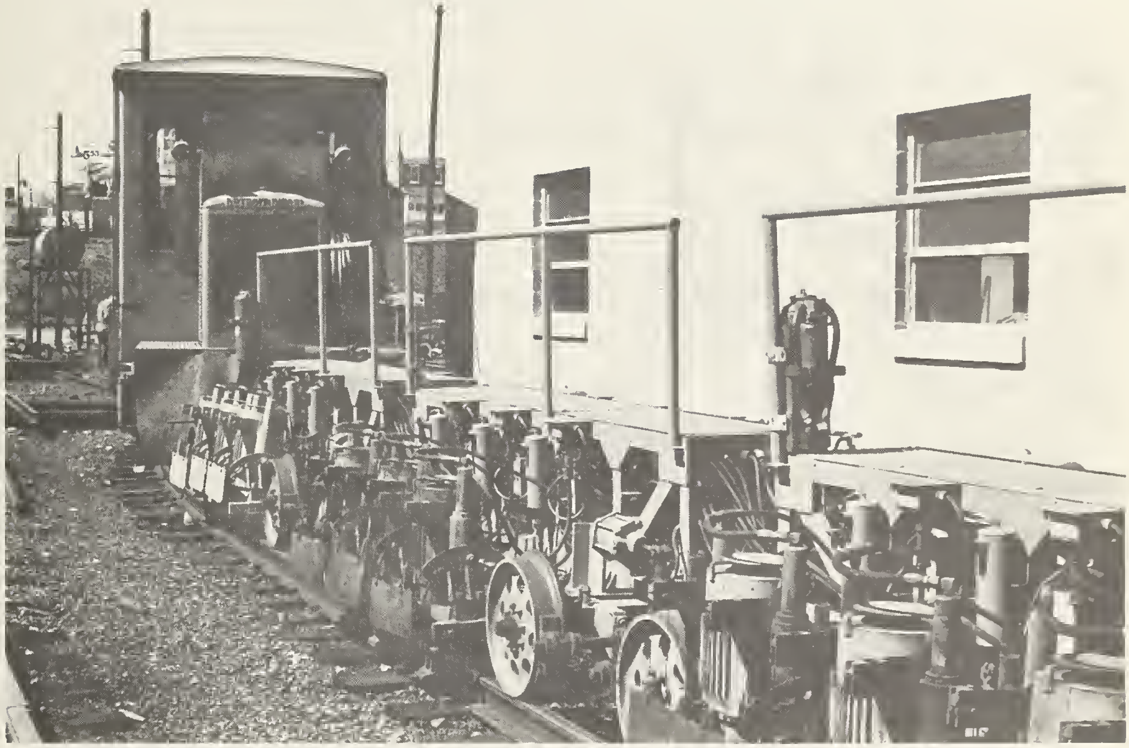


FIGURE 1-5. SPENO RAIL GRINDER

- o Noise generated by the propulsion equipment.
- o Ground-borne vibration produced by operation of the trains in the subway.
- o Structure vibration produced by operation of the trains on the elevated structure.
- o Damping factors of the test wheels.
- o Wheel roughness.

Each of these is discussed briefly in Section 2.

1.3 ECONOMIC ANALYSIS

An extensive effort has gone into the development of the life cycle costs of application of the various noise control methods (with the exception of welded rail). North American rapid transit systems utilizing steel wheel technology were solicited concerning their experience with resilient and damped wheels, rail grinding and wheel truing. In addition, detailed information was requested concerning the techniques, costs and equipment associated with wheel changing, wheel maintenance, wheel truing and rail grinding. A summary of this information was presented in the Initial Test Series Report[3].

Section 6 of this report presents a discussion of the economics of application of the noise control methods to existing rail rapid transit systems. The economic analysis is based on the information solicited from other transit systems and the experience of applying the methods to SEPTA facilities.

2. TEST PROGRAM

The testing program at SEPTA extended from April 1976 to September 1978. The Test Plan[2] developed before initiation of the testing was designed to control as many of the test variables as possible and to thoroughly measure several combinations of test conditions. The basic test plan consisted of: (1) measurement of noise levels before and after applying the four noise reduction procedures, (2) use the wheels and rails in service to apply normal wear for approximately one year, and (3) measurement of noise levels after the wear period and after reapplying the rail grinding and wheel truing to return to conditions similar to those before the wear period.

To obtain information that was applicable to a wide variety of rail transit noise problems, the basic test procedure was used on tangent jointed and tangent welded track both on the elevated structure and in subway, and on a short radius at-grade curve track. Some supplementary measurements were performed at a frog and at station platforms. The specific combinations tested are outlined in Table 2-1.

Note that the SEPTA elevated structure used for the testing is a relatively heavy structure with a concrete deck supporting ballast and tie trackbed. Structures of this design do not result in significant amounts of structure-radiated noise; the noises radiated directly from the rails and the train dominate.

In addition to the measurements outlined in Table 2-1, measurements were also performed on the platforms of a subway station and a surface station. However, because of the difficulty in maintaining consistent operating conditions with the

TABLE 2-1. SUMMARY OF TEST PROGRAM

Track Type	Measurement Locations	Rail Conditions	Wheel Types and Conditions
Tangent B & T with CWR	Car interior and wayside	Worn and ground	Solid steel - new, worn, trued; resilient - new; ring-damped - new & trued
Tangent B & T with Jointed Rails	Car interior and wayside	Worn, new joint bars, and ground	Solid steel - new, worn, trued; resilient - new; ring-damped - new & trued
Switch frog on B & T	Car interior and wayside	Worn	Solid steel - worn & trued; resilient - new
Subway, concrete invert with CWR	Car interior	Worn and ground	Solid steel - new, worn, trued; resilient - new; ring-damped - new
Subway, concrete invert, Jointed Rail	Car interior	Worn and ground	Solid steel - new, worn, trued; resilient - new; ring-damped - new
Short Radius Curve on B & T	Car interior and wayside	Worn and ground	Solid steel - new, worn, trued; resilient - new; ring-damped - new,[1] trued, worn[2]

[1] Wheels with grooves on both sides were tested with rings installed on only the field side, only the flange side, and on both sides; these doubly-grooved wheels were evaluated with wayside measurements only.

[2] Wayside measurements only.

Abbreviations: B & T - ballast and tie trackbed
CWR - continuous welded rail

test trains at platform stops, the variations in noise level for the "same" condition were too great to measure changes in level produced by the noise reduction techniques with any statistical accuracy. Hence, the results from the station platform tests are not included in this report.

In all of the testing, efforts were made to obtain maximum control of test conditions that might influence the noise levels. For example, train speeds were continuously monitored and recorded to provide a permanent record of train speed for use during the analysis of each test. However, as in any field test program conducted over a long time period, there are numerous factors that are beyond control, particularly on an operating transit system whose primary responsibility and concern is reliable revenue service. Some of these are discussed below.

The effort required to instrument the transit structure and the time required to perform the tests limited the testing schedule flexibility and in several instances it was necessary to perform measurements under less than ideal weather conditions. The conditions ranged from hot humid summer weather to very cold winter weather. On a number of occasions the testing had to be terminated early or rescheduled because of rain and on one occasion the testing had to be terminated because of snow. Unfortunately, time and budgetary constraints make it impossible to schedule transit system tests only on fair weather days.

Gusty wind was one potentially significant factor that could not be controlled. No tests were canceled or delayed because of the wind; however, some measurements were taken at times with relatively high winds, not exceeding 25 km/hr. Since the wayside measurements were only 7.5 m from the track

centerline, very high wind speeds would be necessary to have a measurable influence on the noise propagation. Wind noise over the microphone presented little problem because the recordings could be monitored to insure that train noise, not wind noise, was being reported.

The following subsections indicate test tracks, test procedures and schedules used in completing this study.

2.1 TEST TRACKS

All of the test track sections used for this program are located on the Market Street section of the SEPTA system. Since these test tracks have been identified in some detail in two of the previous interim reports, only summary descriptions of the test tracks are given here. The track gauge on SEPTA is 4' 8 1/2".

Tangent Welded Tracks on Ballasted Elevated Structure (TW)

This test section is of timber tie and ballast construction with field welded rails, located on elevated structure between the 60th and 63rd Street Stations. The section was divided into two 100 m segments: the Control Segment and the Test Segment. The Control Segment, serving as a reference track, remained unaltered, except as affected by normal wear, throughout the test program. The Test Segment rails were ground at the beginning and end of the in-service wear period for testing the effects of rail grinding.

Tangent Jointed Track On Ballasted Elevated Structure (TJ)

This section is of timber tie and ballast construction with jointed rail and is located on the elevated structure between the 56th and 60th Street Stations. The section was divided into three 100 m segments: A, B, and Control. The Control

Segment remained as is throughout the test program and the remaining two segments were used to test the acoustical effects of changing joint bars to improve joint alignment and the effects of rail grinding.

Short Radius Curve, Ballasted Track At Grade (TURN)

This test track is the inside turnaround track at the 69th Street Station, a short-radius curve on which the SEPTA revenue trains normally create high levels of squeal noise. The section is composed of timber tie and ballasted track at-grade construction with jointed low rail, and welded high rail. The radius of curvature is approximately 43 m. The track was divided into two segments: Control and Test. The Control Segment was to remain unaltered during the test program and the Test Segment rails ground twice (with a one year interval between grinding). This procedure allowed direct measurements of the effects of rail grinding. However, the Control Segment was inadvertently ground smooth during the early tests.

Tangent Welded Track In Subway (SUB 1)

This test section is composed of field welded rail fastened to timber half ties embedded in the concrete invert of the subway structure. The section, located just east of the 22nd Street Subway-Surface Station, consisted only of a test segment of track approximately 100 m long.

Tangent Jointed Track In Subway (SUB 2)

This test section is the same as SUB 1 only of jointed track construction. The Test Track Segment is located just east of the 19th Street Subway-Surface Station.

Switch Frog

A switch frog on the ballasted elevated structure just east of the 63rd Street Station.

Elevated Station

The 63rd Street Station. The station has ballast and tie track with jointed rails.

Subway Station

The 15th Street Station. The station has continuous welded rail on concrete invert.

2.2 WAYSIDE AND CAR INTERIOR NOISE TESTS.

The test program has been described in detail in the interim reports and is only briefly outlined here. The measurements of the wayside and car interior noise produced on the various test tracks for the various operating conditions were divided into seven sequential phases. The results of the first three test phases were presented in the Initial Test Series Report[3] and the results of the last four test phases presented in the Second Test Series Report[4].

The test program was arranged to provide measurements of wayside and car interior noise; before and after rail grinding, before and after wheel truing, and with resilient and damped wheels in new and worn condition. The test schedule included a wear period of approximately one year to allow evaluation of the noise control methods before and after wear; to develop economic information on application of the methods; and to determine problems unrelated to noise control that might have a bearing on application of the noise control methods. As discussed in Section 1.1.1, problems were experienced with all

three types of resilient wheels that forced removing the wheels from the program before the end of the wear period.

The seven test phases are briefly described below:

Phase I (June-July 1976)
The Phase I measurements of wayside and car interior noise were performed with the new standard wheel train (Cars 755/756) and the worn standard wheel train (Cars 613/623). The tests were designed to verify the noise measurement and reduction procedure; establish variation between Test and Control Track segments; document noise levels produced by new and worn standard wheels on worn and ground rail; and investigate differences between new lathe turned wheels and standard wheels trued with a milling cutter type of truing machine.

Phase II (October 1976)
The Phase II measurements of wayside and car interior were performed after the three sets of resilient wheels had been installed. The tests included the resilient wheels and both the worn and trued standard steel wheels on all types of track both before and after rail grinding.

Phase III (July 1977)
Phase III was an abbreviated set of noise measurements performed approximately six months after Phase II to determine the effects of in-service wear on the wheels and rail. Originally Phase III was to include only car interior noise measurements; however, because the problems experienced with the resilient wheels forced removing all of the resilient

wheels from the study after Phase III, the Phase III testing was expanded to include wayside noise measurements at the TW and TURN test tracks.

Phase IV (November 1977)
The original purpose of Phase IV was to evaluate all combinations of worn wheels and worn rails after a one year in-service wear period by measuring both wayside and car interior noise. However, of the five original test trains, only the worn standard wheels and the new standard wheels were still in operation. It is at this point that the ring-damped wheels, new standard steel wheels with ring-dampers installed, were added to the study. Hence, the Phase IV tests included the worn standard wheels, the new standard wheels which had been used in service, the ring-damped wheels with rings installed, and the ring-damped wheels with the rings removed. The ring-damped wheels used at this point were new with no in-service wear. The tests were performed on the TW, TJ, TURN, SUB 1, and SUB 2 test tracks.

Phase V (December 1977)
After Phase IV all of the test segments of the test track rails were ground and the acoustical measurements of Phase IV repeated.

Phase VI (December 1977)
After Phase V all of the test wheels, including the ring-damped wheels, were trued and car interior and wayside noise tests were performed on the TW and TURN test tracks, which had the Test Segments in newly ground condition and the Control Segments in worn condition. Car interior measurements were performed at the TJ test track.

Phase VII (September 1978)

Because of the success of the ring-damped wheels in reducing squeal noise as observed during the Phase IV, V and VI tests, the testing was expanded to include a final test series on the TURN test track with a second set of ring-damped wheels. The second set of ring-damped wheels had grooves cut on the flange side and the field side of the wheel. This final test series included both sets of ring-damped wheels with the rings installed and without the rings.

2.3 PROPULSION EQUIPMENT NOISE TESTS

On most transit cars at normal operating speed, noise generated by the propulsion equipment, primarily the traction motors and gear boxes, is of the same order of magnitude as the wheel/rail noise. There are some instances where other noise sources may be important components, but wheel/rail noise and propulsion equipment noise generally dominate.

The purpose of all of the noise control methods tested in this study is to reduce the wheel/rail noise. Obviously, if the noise from the propulsion equipment dominates the overall noise levels, it is impossible to determine the effectiveness of the noise control methods in reducing wheel/rail noises from direct measurements of car interior and wayside noise.

To help determine the relative contributions of wheel/rail noise and propulsion equipment noise to the overall noise level, noise measurements were performed with the cars supported on blocks and the wheels spinning freely. This procedure essentially reproduces the test conditions with the wheel/rail noise removed. As discussed in Section 3, the wheel/rail noise was found to dominate the overall noise levels. However, the level of propulsion equipment noise limited the

reduction of wheel/rail noise that could be observed in this study. More important, obviously, is that net reduction in overall sound level achieved by applying the 5 techniques is limited without treatment to propulsion system.

2.4 GROUND-BORNE VIBRATION TESTS

At many transit systems the structure-borne vibration created at the wheel/rail interface results in noise and vibration intrusion inside adjacent structures. The vibration produced at the wheel/rail interface by the wheels rolling on the rails is transmitted from the transit structure through the ground to nearby structures. The vibration of the building structure is sometimes perceptible as mechanical motion and more often appears as a low frequency rumbling noise radiated from the room surfaces inside buildings, i.e., as structure-borne noise.

The acoustical tests of the methods to reduce wheel/rail noise presented a unique opportunity to evaluate the effectiveness of the same methods at reducing the vibration levels. Vibration measurements were performed simultaneously with several of the acoustical tests of Phases I and II. The vibration data were collected by personnel of the Port Authority of New York and New Jersey at measurement locations at the Test Segment of the TW test track and the tangent welded subway test track (SUB 1).

The results of the vibration measurements are presented in Section 5. The testing included measurements with new resilient wheels, worn standard wheels and trued standard wheels, all on tangent welded track. In the subway, tests were made with the rails worn and recently ground, and on elevated structure the tests were with recently ground rails only.

2.5 WHEEL VIBRATION DECAY RATE

One of the primary design goals for the resilient and damped wheels is the achievement of high damping factors to reduce vibration amplitudes and thereby reduce noise radiation. The higher the damping factor of the wheels the less likely squeal will occur on short-radius curves.

A short series of tests were performed to measure the loss factors as a function of frequency using the resilient, ring-damped and standard wheels. The method used was to measure the vibration decay after impacting the wheels. The results of these tests were presented in Section 5 of the Second Test Series Report[4]. Basically, the tests showed that wheel sequal is highly correlated to internal damping of the wheels. All of the resilient wheels have substantially greater damping than the standard steel wheels. The ring-dampers were shown to create substantial damping above about 1400 Hz.

2.6 WHEEL AND RAIL ROUGHNESS

In a previous study, theories of the mechanisms of wheel/rail noise generation were developed[6]. The basic premise of the roar noise theory is that the noise produced is directly related to the roughness spectra of the wheels and the rails. For the purpose of verifying this theory, efforts were made in this study to perform measurements of wheel and rail roughness. Although successful measurements of wheel roughness were performed, the attempts at measuring rail roughness on in-service rail were unsuccessful. A discussion of the roughness results was presented in the Initial Test Series Report[3].

3. PROPULSION EQUIPMENT NOISE TEST RESULTS

The overall purpose of this program is to evaluate the reduction of wheel/rail noise that can be achieved in service on an operating transit system. For most transit cars the noise from the propulsion equipment is on the same order of magnitude as the roar noise generated by the wheels rolling on the rail - the wheel/rail noise. Since on the SEPTA cars the propulsion motors and the gearboxes cannot be disengaged from the axles, the reduction of wheel/rail noise that can be observed in this study is limited by the noise from the propulsion equipment.

The noise from the propulsion equipment was evaluated by supporting the test cars on blocks such that the wheels could spin freely. With the wheels spinning freely and all of the auxiliary equipment operating, it is possible to duplicate the conditions of the moving train tests without wheel/rail noise. The only differences that may have some influence on the noise levels are the train being approximately 10 cm higher above the trackbed than normal and the fact that the gears operate at a no-load condition.

The change in the train elevation may slightly increase the wayside levels by reducing the amount of noise "trapped" under the car and absorbed by the ballast. Since the elevation change is relatively small, the influence on the noise levels should be small.

The fact that the propulsion equipment is operating under the no-load condition also has only a minor influence on the noise level. During normal operation with the gears and motors loaded, there may be some additional gearbox noise;

however, the propulsion system noise level performance tests for the BART, WMATA Metro and new CTA cars show that in most cases the gearbox noise is less than or at most comparable with, the noise from the propulsion motors. The motors generate the same noise whether loaded or unloaded because the predominant sources of noise are the cooling fan and normal windage noise, noise sources which are independent of load. The net result is that overall propulsion equipment noise is only slightly, if at all, influenced by load.

The results from the car-on-blocks tests with the SEPTA cars are presented in Figures 3-1 and 3-2. Analysis of the propulsion equipment noise revealed that the propulsion equipment noise is dominated by a tonal noise at the blade passage frequency of the traction motor cooling fans. In all of the SEPTA data presented in Figures 3-1 and 3-2, the effects of the pure tone have been removed. With the pure tone included, the propulsion equipment noise is 2 to 7 dBA higher both inside the cars and at the wayside. In addition, in the acoustical analysis of the SEPTA tests with the trains operating on tangent track, a tunable notch filter was used to remove the effect of the tonal noise. Since the traction motor cooling fans are located on the motor shafts, and there is a direct drive between the traction motors and the wheels, the frequency of the tonal noise is proportional to train speed.

Figures 3-1 and 3-2 include data for similar propulsion equipment noise tests with BART[7], TTC[8], CTA[9,10] and WMATA[11] cars. The CTA data include the average wayside propulsion equipment noise from the 6000, 2000 and 2200 series cars and from the new 2400 series cars being built by the Boeing Vertol Company. The data for the TTC and existing CTA cars were taken inside the car shops and adjusted for reverberant and

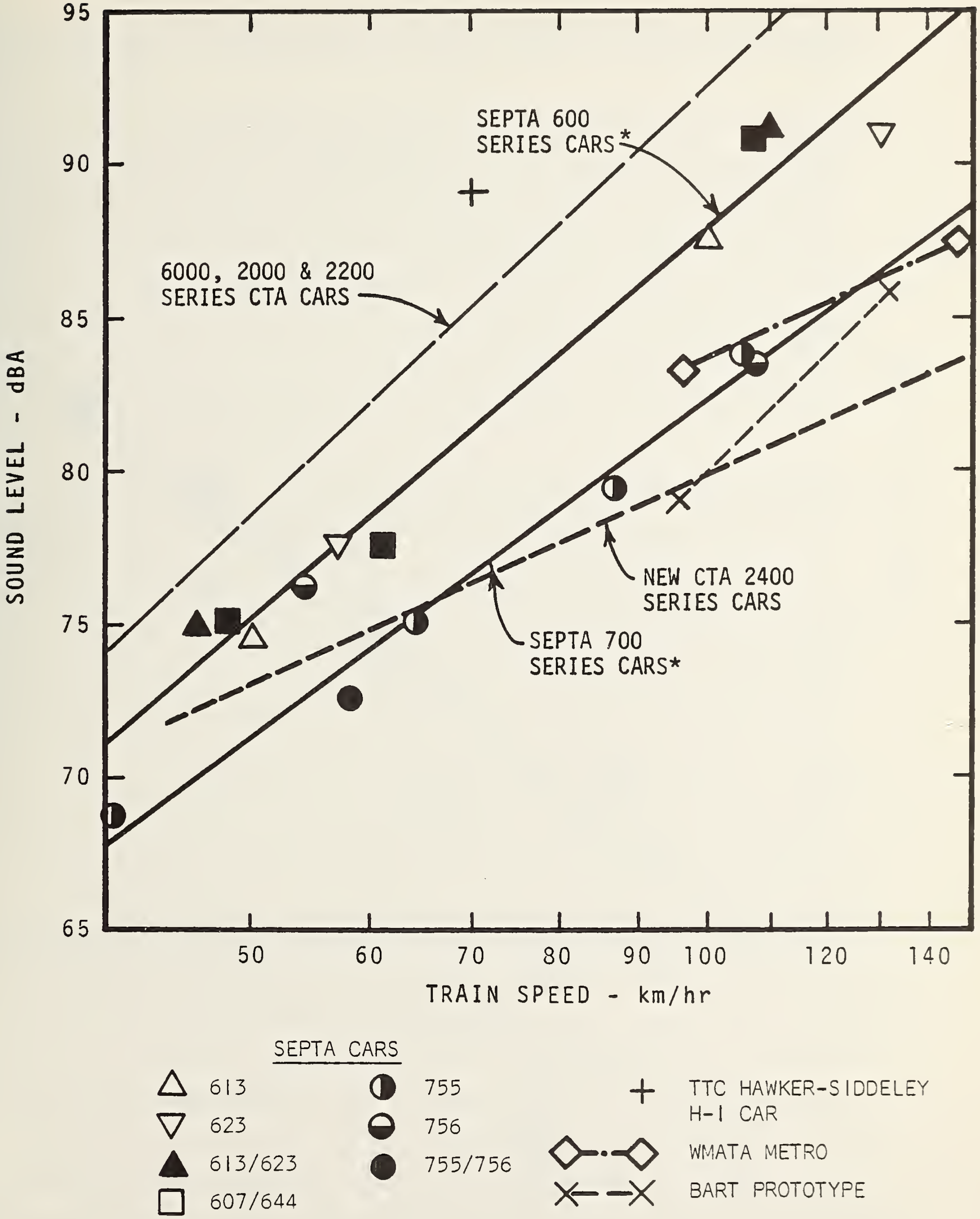


FIGURE 3-1. WAYSIDE NOISE LEVEL FOR PROPULSION EQUIPMENT AS A FUNCTION OF SPEED - 7.5 METERS FROM TRACK CENTERLINE
*[PURE TONE COMPONENTS REMOVED FROM SEPTA DATA]

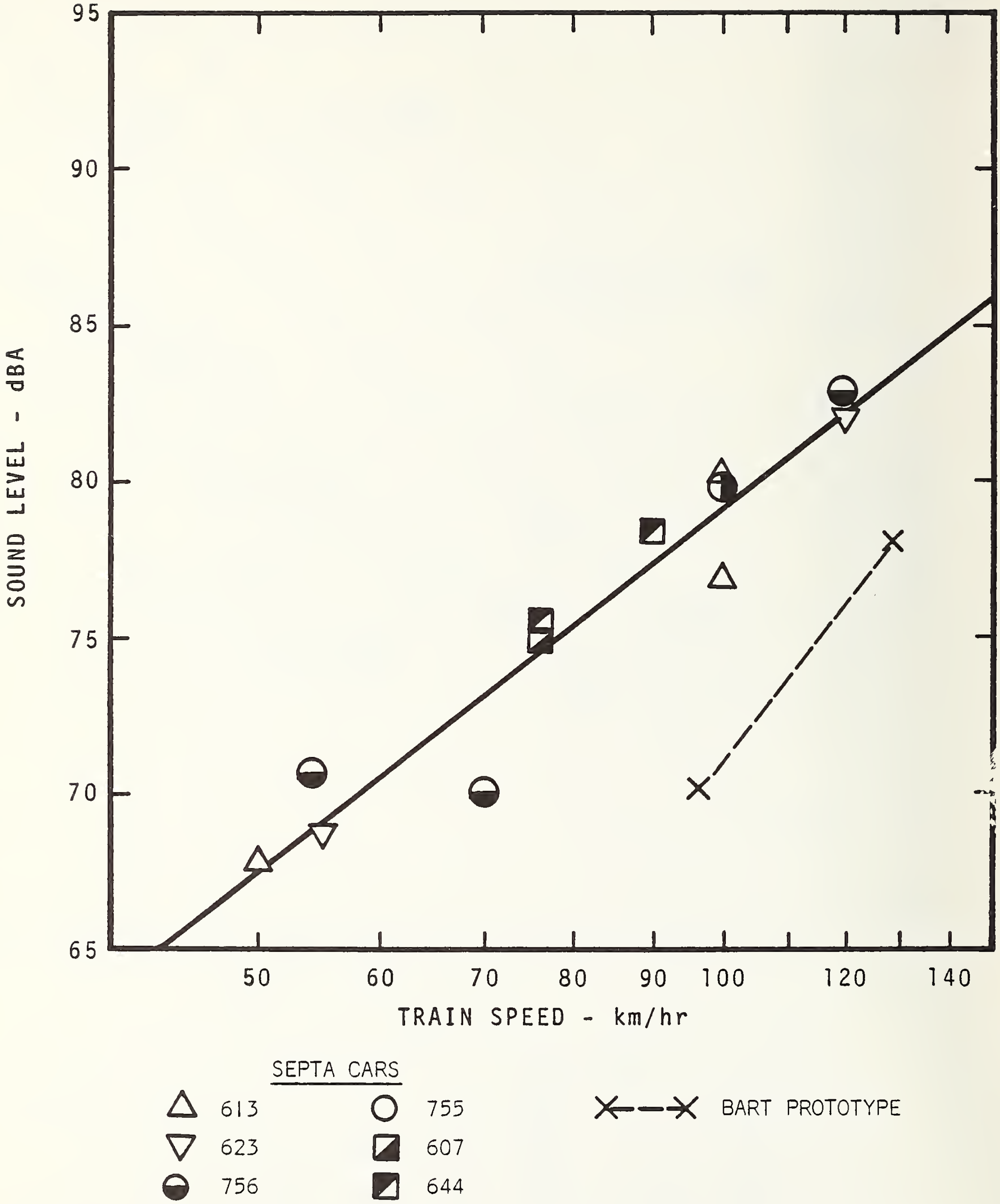


FIGURE 3-2. LEVELS OF PROPULSION EQUIPMENT NOISE AS A FUNCTION OF SPEED - CAR INTERIOR [PURE TONE COMPONENTS REMOVED FROM SEPTA DATA]

reflected sound to correspond to the levels outside on ballast and tie tracks.

It should be noted that only for the SEPTA data have the pure tone components of propulsion system cooling fan noise been removed from the data. If the pure tones were not removed, the wayside propulsion equipment noise with the SEPTA 600 series cars would fall between that of the TTC car and the existing CTA cars. Even with the pure tone included, the wayside noise levels with the 700 series SEPTA cars (the married pair cars) are several dBA below the levels of the existing CTA cars and the TTC cars.

At high speeds the wayside propulsion equipment noise for the new CTA 2400 series cars is considerably below the levels of all the other cars for which data is available. This is largely a function of the traction motor cooling system design on the new CTA cars. The 2000 and 2200 series cars have self-ventilated traction motors that create noise levels strongly dependent on train speed. The new 2400 series cars have a forced air cooling system to cool the traction motors. This design is inherently quieter than cooling by shaft-mounted fans except at low speeds. At low speeds the forced air cooling system may produce enough noise to be dominant. Note that the CTA 6000 series cars, all of which were purchased before 1959, also have forced air propulsion motor cooling. The fact that the 6000, 2000 and 2200 cars create essentially the same levels of propulsion noise indicates that even with forced air cooling systems, the overall acoustic aspects of the transit car must be carefully considered in determining expected noise levels.

For the car interior noise only data from a BART prototype car and the SEPTA cars are available. The data indicate that the car interior noise levels are equivalent for the 600 series

and the 700 series SEPTA cars, while the propulsion equipment noise inside the BART car is substantially lower. If the pure tone components had not been removed from the SEPTA data, the difference would be approximately 10 dBA. Since the sound insulating properties of the production BART cars are superior to those of the prototype car, the difference would be even greater with the production cars.

4. ACOUSTICAL RESULTS

4.1 INTRODUCTION

As outlined in Section 2, a major part of this study was performance of extensive acoustical tests to evaluate the effectiveness of rail grinding, wheel truing, resilient wheels, damped wheels, and welded rail at reducing wheel/rail noise. The detailed acoustical results are presented in the two test series reports[3,4]. The purpose of this Section is to present a summary of the results observed at SEPTA and comparisons of these results with studies performed on other transit systems, and to indicate some generalized conclusions regarding the acoustical effectiveness of the four noise reduction methods.

The results from use of rail grinding, wheel truing, resilient wheels and damped wheels to reduce wheel/rail noise are discussed in Section 4.2. The test program included extensive measurements with the test trains on both jointed and welded tangent rails. Hence, although changing from jointed rails to welded rails was not one of the noise control procedures specifically implemented during this study, the measurement program provided extensive data that can be used to compare noise levels on jointed and welded rails. Section 4.3 presents comparisons and discussion of the noise levels on jointed and welded rails.

Based on the car-on-blocks data presented in Section 3, at 60 km/hr the propulsion equipment noise inside the cars is approximately 70 dBA for both types of cars. At the wayside the level is 78 dBA for the 600 series SEPTA cars and 74 dBA for the 700 series SEPTA cars. On the TW test track the overall wayside levels with the 600 series cars ranged from 3 to

15 dBA above the propulsion equipment noise levels, and with the 700 series cars the range was 4 to 18 dBA. When the difference between the propulsion equipment noise level and the overall noise level is only 3 to 4 dBA, the propulsion equipment noise and the wheel/rail noise are approximately equal. Conversely, when the difference between overall noise level and propulsion equipment noise level is 15 to 18 dBA, the propulsion equipment noise contributes insignificantly to the overall noise level and the overall noise level is dominated by wheel/rail noise.

Comparisons of the test data on the TW test track and the levels of propulsion equipment noise indicate that the propulsion equipment noise limited the reduction of wheel/rail noise that could be observed in this study. The levels on the TJ test track were higher than on the TW test track because of the rail joint impact noise. As a result, the propulsion equipment was a less significant component of overall noise level for the jointed test track.

4.2 OVERVIEW OF MEASUREMENT RESULTS

This Section presents a summary of the test results with each of the noise control methods and compares the results at SEPTA with results that have been obtained at other transit systems. Only summary results are presented in this Section; the specific reductions for various individual test conditions observed in this study are tabulated in the Appendix. The Appendix also includes a set of graphs of the average A-weighted levels for each combination of wheel and rail condition.

Typically, the test results on each day of testing were very consistent. On only rare occasions did the data points for a specific train and test track combination on a given day

vary more than ± 1 dBA from the best fit line of sound level as a function of speed. Most of the data analysis was performed after normalizing all of the sound levels to 60 km/hr. The pooled standard deviation for all of the testing on tangent track is 1.0 dBA. This indicates that when comparing mean values to evaluate the effect of the test parameters, if the mean values vary by more than 1.3 dBA, one can be 95% confident that the change is due to factors other than the randon fluctuations of sound level (assuming the mean includes six passbys).

In some cases, several independent tests were performed with the same combinations of wheel and wear condition. In most cases the variations between the independent tests with similar test conditions are relatively small, typically 1 to 2 dBA. However, there are some tests where significant variations were observed. An example is the wayside levels on the TW test track with standard wheel test trains. In Test Series #1 the average level with wheels worn about one year was 83.2 dBA, while in Test Series #2 with the same nominal test conditions the average level was 86.4 dBA. As discussed in the interim reports, high quality instrumentation was used for the testing and extreme care was taken to accurately calibrate the recorded signals. It is clear that the variations in sound level were caused by some variation in the test conditions. The most likely cause for this variation in noise level is changes in the condition of the wheels.

Since variations as large as 7 dBA were found on different test days when the test conditions were nominally the same, some care must be taken when evaluating the noise reduction achieved in this study. When possible, the test program was designed to minimize the effects of uncontrollable factors. For example,

the use of control and test segments on the elevated structure test tracks helped reduce the influence of the uncontrollable factors when evaluating the effects of rail grinding. Unfortunately, it was not possible to include similar direct comparisons for all of the test variables.

The occurrence of wheel flats can create sudden changes in both wayside and car interior noise levels. The impact noises from recent wheel flats are clearly audible; however, after the wheel flat has aged, it is no longer an identifiable component of the wheel/rail noise, although it can still be the cause of significant increases in noise level. The same general mechanism may occur with spalled or shelled areas where surface stresses result in pitting or indenting of the surface of the wheels. After several months of revenue service, wheel flats and spalled or shelled areas were all observed on the test wheels. In one test series an emergency stop resulting in wheel sliding was actuated by a signal failure caused by the cold weather. The emergency stop resulted in wheel flats on one of the test cars which in subsequent passby tests created clearly audible impact noise during portions of the passbys. In the data analysis an effort was made to avoid the obvious wheel flat noise; however, wheel flats certainly resulted in some noise level variations. It is unlikely that changes in the condition of the rail surface or variations in meterological conditions could result in the significant changes in wayside noise levels observed from some tests.

Figures 4-1 through 4-6 present the A-weighted results measured on the tangent ballast and tie test tracks as a function of train speed. The data has been arranged on these figures to reflect the variations of sound level as a function of wheel and rail conditions. These figures indicate the basic

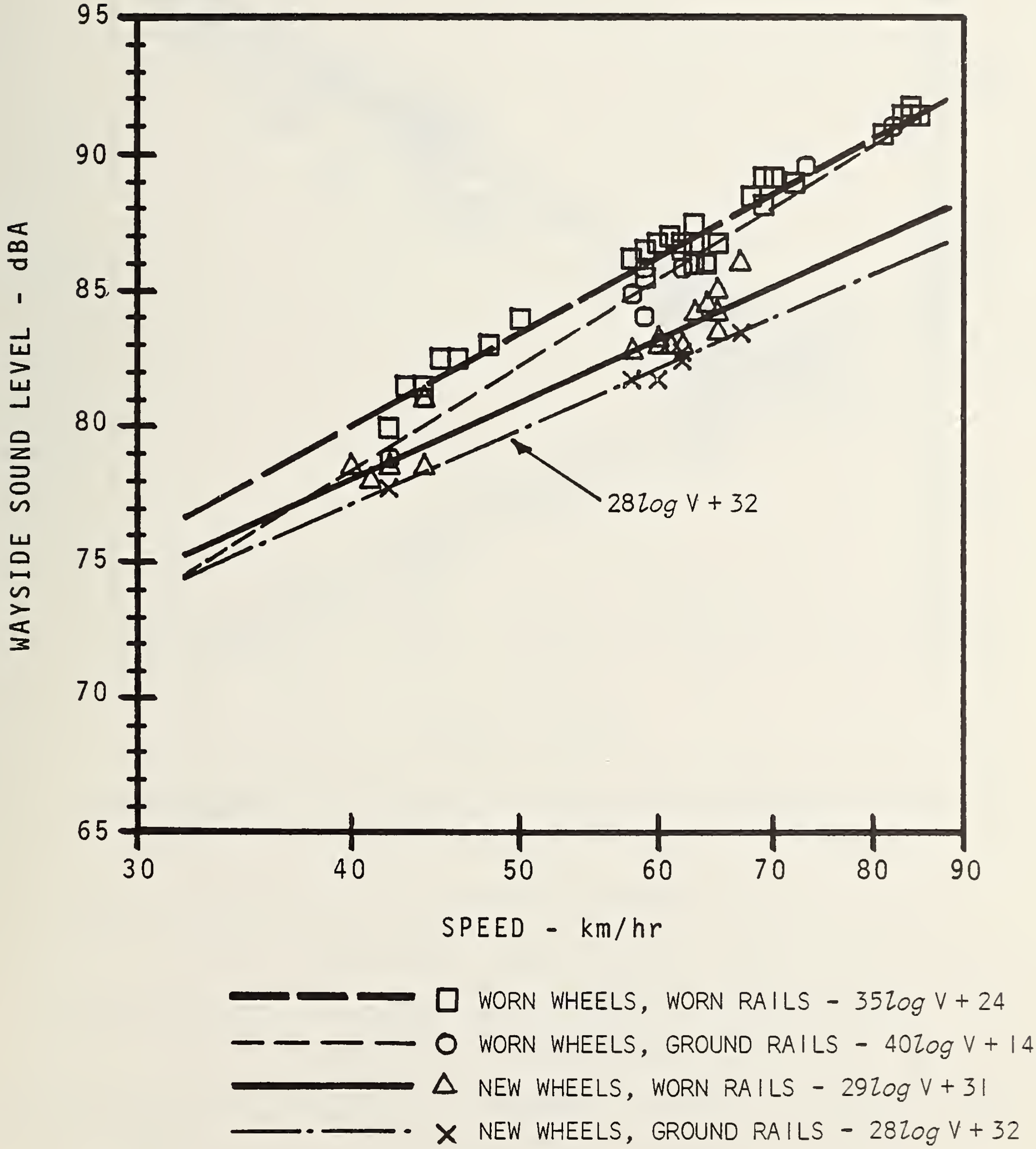


FIGURE 4-1. WAYSIDE SOUND LEVELS AT TW TEST TRACK WITH NEW AND WORN WHEELS AND WITH WORN AND GROUND RAIL

TEST SERIES 2 - 7.5 m FROM TRACK CENTERLINE

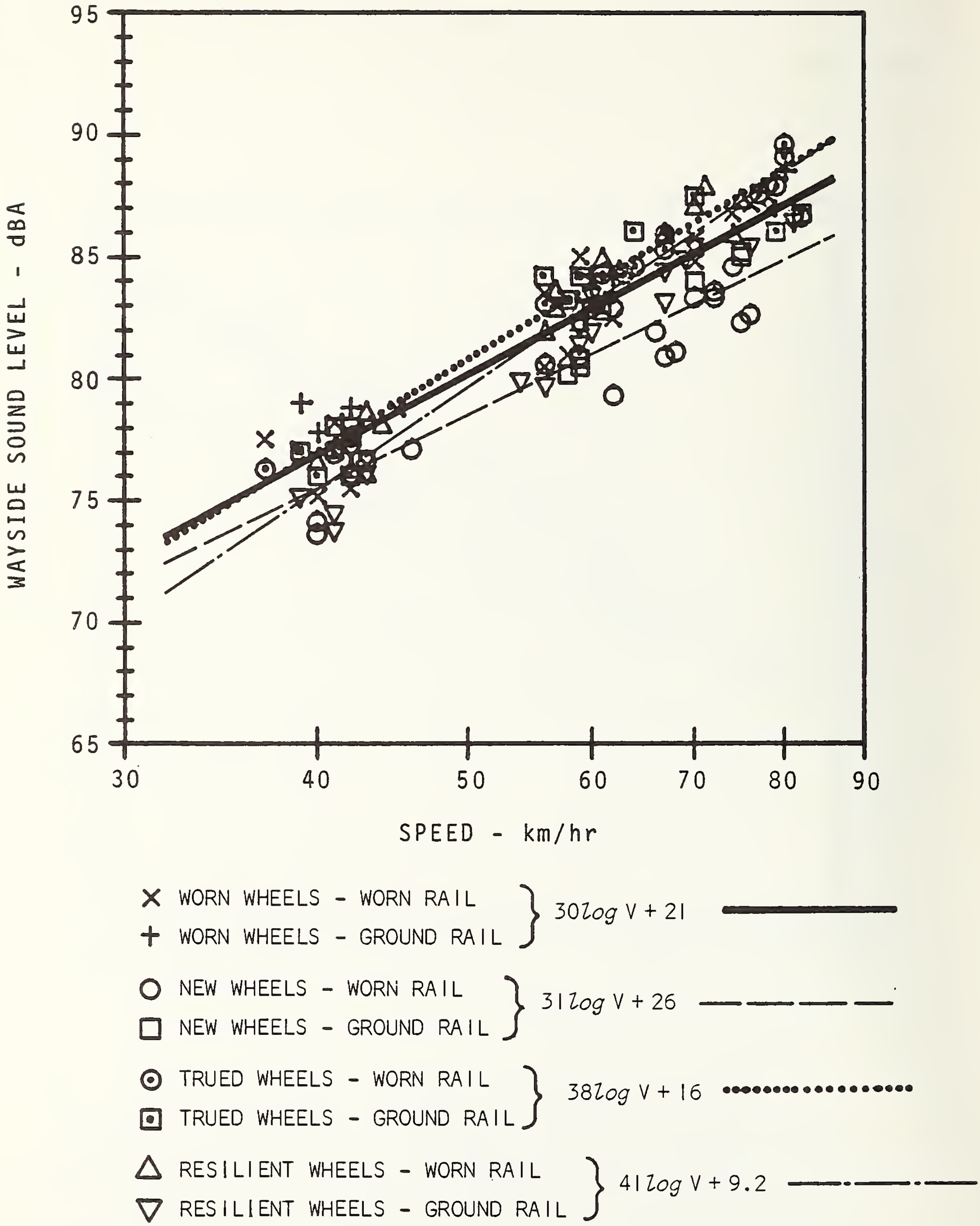


FIGURE 4-2. WAYSIDE SOUND LEVELS AT TW TEST TRACK

TEST SERIES 1 - 7.5 m FROM TRACK CENTERLINE

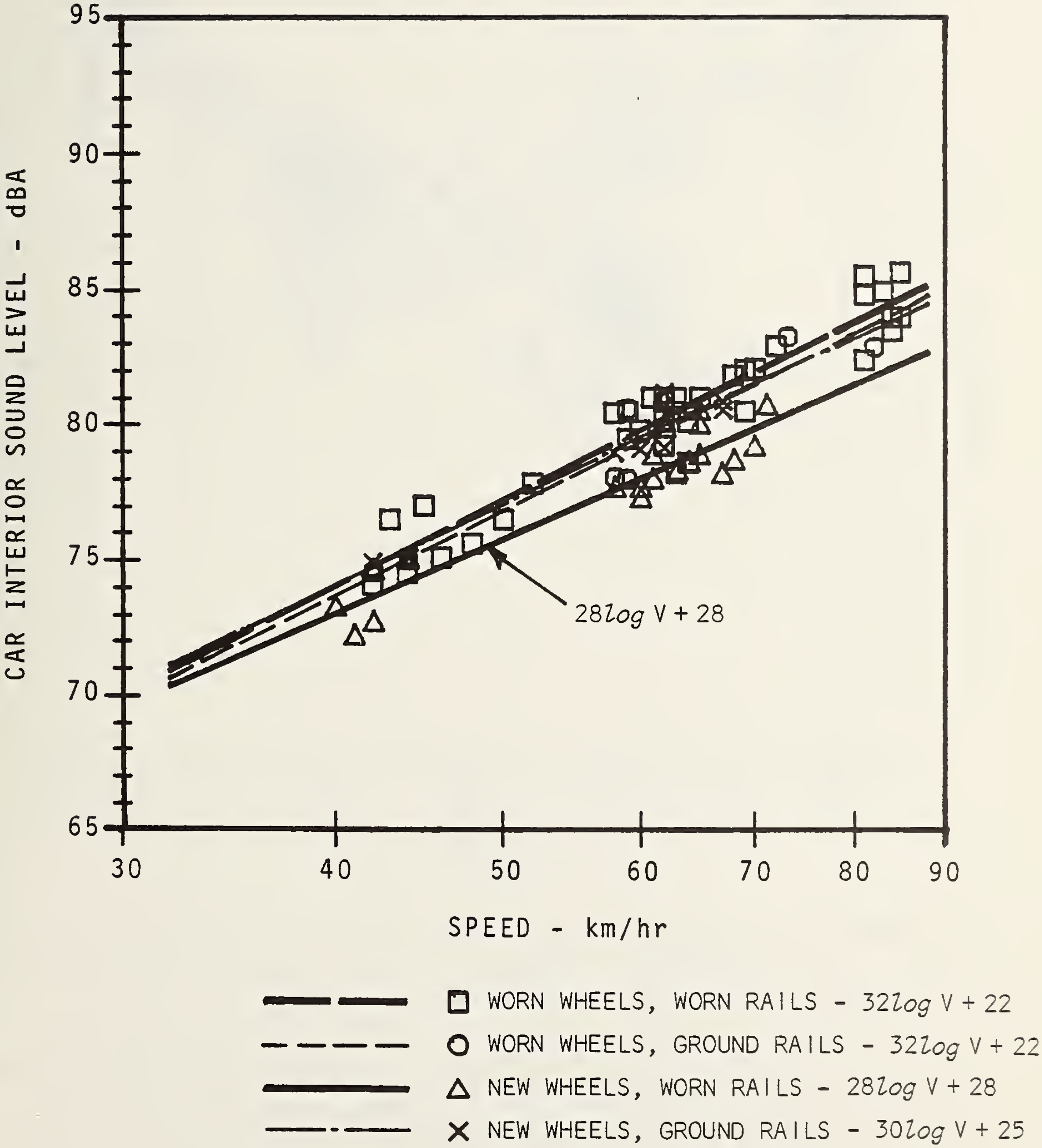


FIGURE 4-3. CAR INTERIOR SOUND LEVELS ON TW TEST TRACK WITH NEW AND WORN WHEELS AND WITH WORN AND GROUND RAILS - TEST SERIES 2

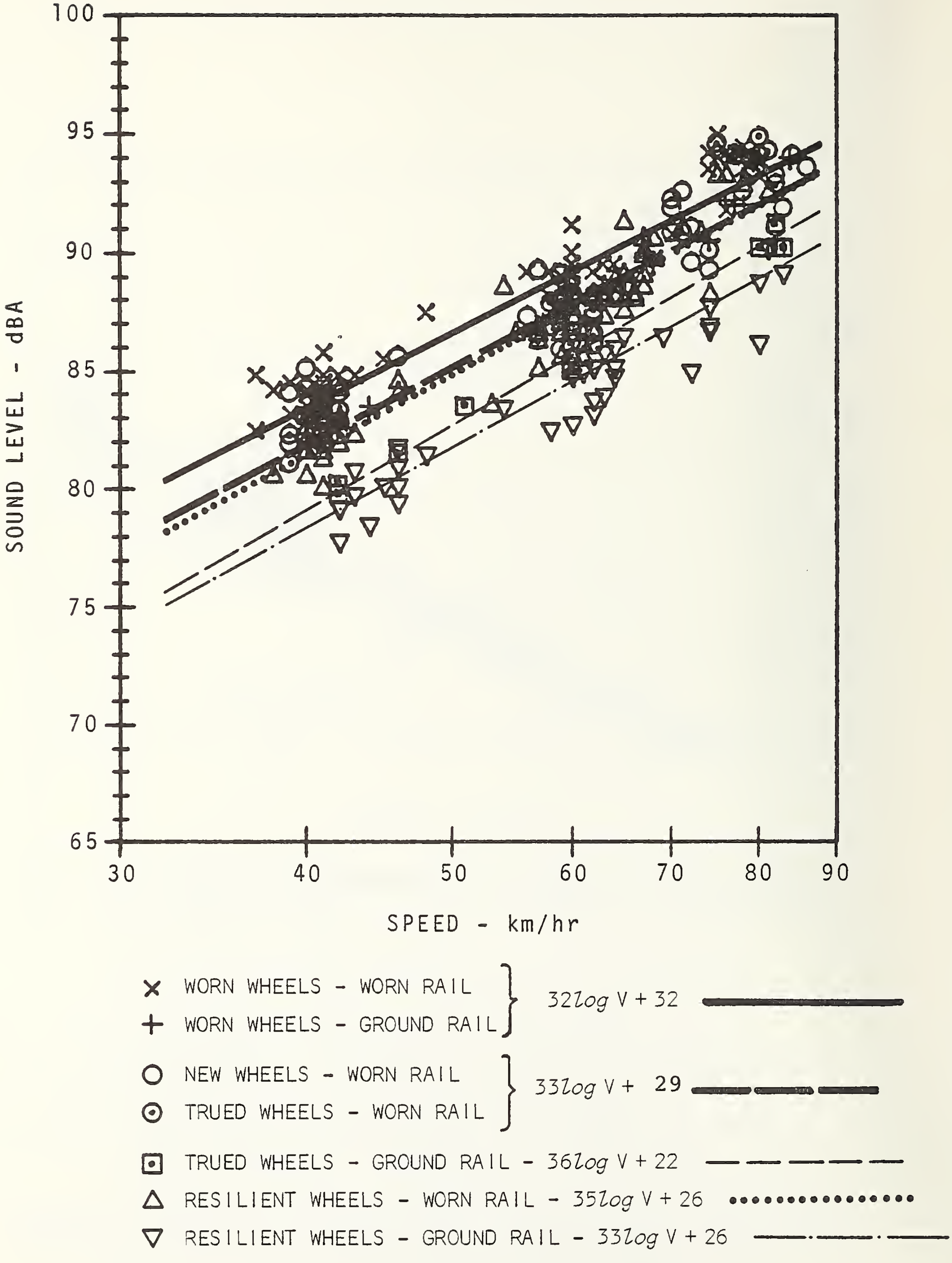
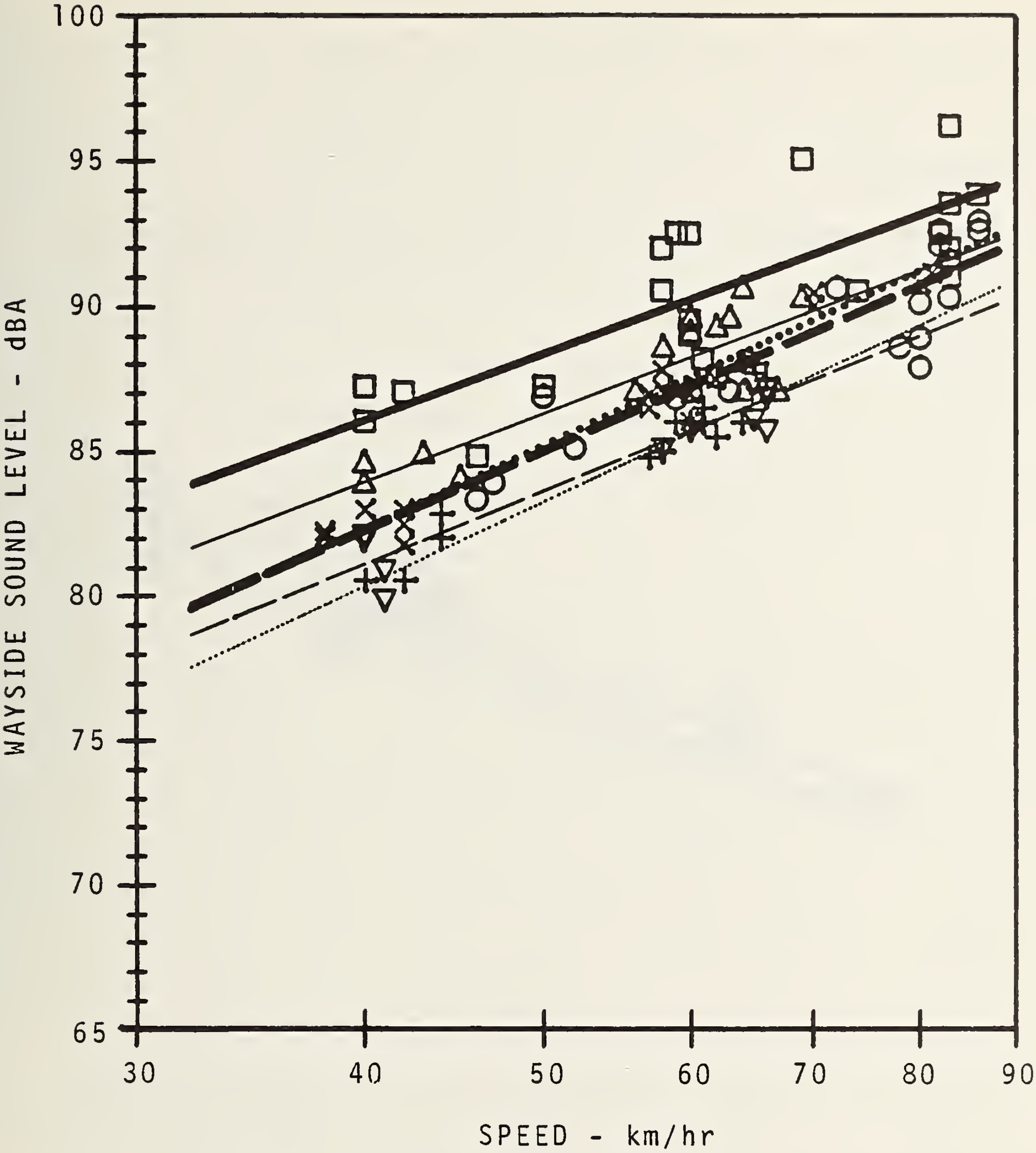


FIGURE 4-4. WAYSIDE SOUND LEVEL AT TJ TEST TRACK

TEST SERIES 1 - 7.5 m FROM TRACK CENTERLINE



□ RAIL WORN 2 YEARS, WORN WHEELS - 23*log* V + 50

△ RAIL WORN 2 YEARS, NEW WHEELS - 24*log* V + 46

○ RAIL WORN 1 YEAR, WORN WHEELS - 28*log* V + 37

▽ RAIL WORN 1 YEAR, NEW WHEELS - 26*log* V + 40

× GROUND RAIL, WORN WHEELS - 29*log* V + 36

+ GROUND RAIL, NEW WHEELS - 30*log* V + 36

FIGURE 4-5. WAYSIDE SOUND LEVELS AT TJ TEST TRACK

TEST SERIES 2 - 7.5 m FROM TRACK CENTERLINE

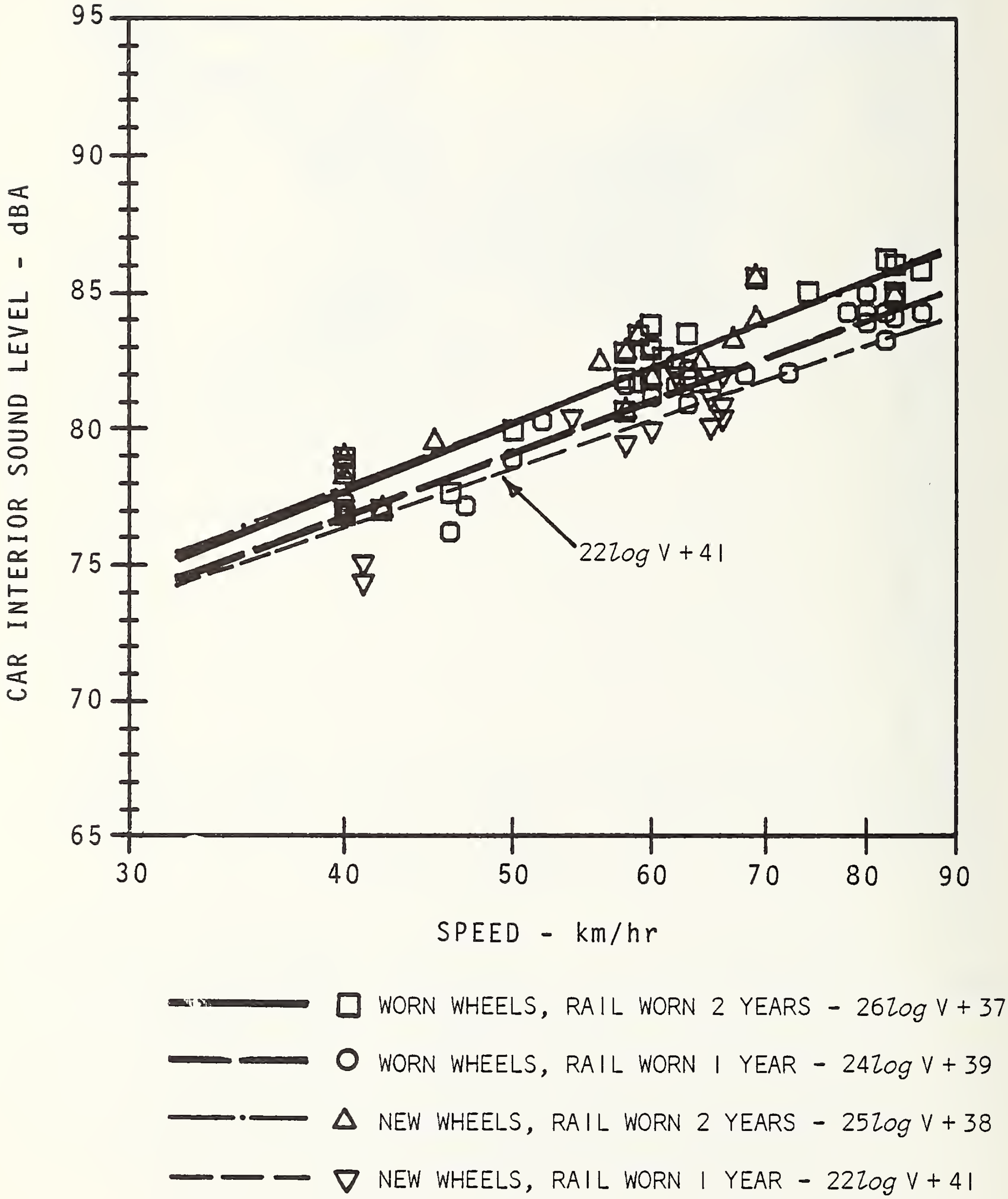


FIGURE 4-6. CAR INTERIOR SOUND LEVELS ON THE TANGENT JOINTED TEST TRACK WITH NEW AND WORN WHEELS AND WITH RAILS WORN 1 AND 2 YEARS - TEST SERIES 2

results of this study and are referenced in the following discussion of the effects of rail grinding, wheel truing and resilient wheels. The tabulations in the Appendix also present data indicating the basis of points presented in the discussions.

The graphs illustrate that for the different test conditions, at a particular operating speed, the sound levels inside the cars varied over a range of approximately 5 dBA while a larger variation, 8 to 10 dBA, was observed for the wayside sound levels. Further, the graphs show that with only a few exceptions the data has speed dependence of 25 to 35 *log* V. Note that the data from the welded test track has a consistently higher slope than the jointed track data.

The relative insensitivity of the car interior noise is due to two factors. First, the car body sound insulation characteristics are such that there is significantly greater attenuation of the high frequencies than of the low frequencies. Also the propulsion equipment noise makes a significant contribution to the overall sound level. With increasing speed the spectrum of the propulsion equipment noise and to a lesser degree the wheel/rail noise shifts to the higher frequencies which are better attenuated by the car body.

4.3 RAIL GRINDING

4.3.1 SEPTA Results

Basically, the SEPTA data showed measurable but small reductions on both tangent track and curved track.

TW Test Track

For most test conditions the before/after rail grinding tests at the TW test track showed relatively small changes in noise levels, in many cases the change in noise level was too small to be separated from the normal random variation of the noise level data.

Figure 4-1 presents the Test Series 2 wayside noise data for the TW test track. This figure shows the best fit lines

for the results with worn wheels and with new wheels. Note that the worn and ground rail results are essentially equivalent; the ground rail results in a maximum of 1.0 to 1.5 dBA reduction. Figure 4-2 presents the data and best fit lines for Test Series 1 at the TW test track. In this case the best fit lines combined the worn rail and ground rail data since the differences between worn and ground rails were small and the main differences resulted from the variations in wheel condition.

The one time that significant differences in the noise levels on the ground and worn test segments were observed was during the Phase VI tests after truing the wheels of the three test trains. The noise levels at most of the test tracks increased after wheel truing, apparently because the wheels still had the cutter marks from the truing machine on the tread surface. However, on the TW test track, after wheel truing, the wayside noise levels increased about 4 dBA on the Control Track Segment and stayed essentially the same on the Test Track Segment. Thus, after wheel truing the wayside noise levels on the worn track were approximately 5 dBA higher than on the recently ground test track. Since this was an isolated case, it is not appropriate to use it in forming general conclusions. The general conclusion from the rail grinding test is that grinding of worn welded rail without observable corrugations results in negligible reductions of wheel/rail noise for ballast and tie track.

TJ Test Track

Rail grinding had a small but measurable effect in reducing the noise levels at the TJ test track. Before the rails were ground, the joint bars were changed on one of the Test Segments to attempt to improve the joint alignment and reduce impact noise at the joints. Changing the joint bars resulted in a maximum of 1 dBA reduction of wheel/rail noise implying that the joint alignment was only marginally improved by the change of joint bars.

The Test Segment of the TJ test track were ground smooth in Test Series 1 and in Test Series 2. After the first grinding the noise levels were reduced an average of about 3 dBA at the wayside; see Figure 4-4. For the car interior the reduction was 1 to 2 dBA. The noise reduction could be due to reducing road noise by grinding the rails or reducing impact noise by improving joint alignment.

After the one year wear period, the noise levels on the Test and Control Segments of the TJ track had not changed significantly. The noise levels were still approximately the same as before the wear period and the wayside noise level on the Control Segment was still about 3 dBA higher than on the Test Segment. Since the rail grinding in Test Series 2 did not result in significant noise level reductions (see Figure 4-5), the data indicate that the rail grinding in Test Series 1 improved the condition of the test tracks, however, in the one year wear period the rail surface and joint alignment did not deteriorate enough to be measurably improved by rail grinding.

Subway Test Tracks

The tests before and after grinding both the jointed and welded subway test tracks in Test Series 1 indicate significant, consistent noise reduction was achieved with the rail grinding. With the resilient wheels and new standard wheels, the average reduction was 3 dBA. However, with the worn standard wheels no significant change in noise level was achieved with rail grinding.

In contrast with the results of Test Series 1, the before/after rail grinding results of Test Series 2 do not show any consistent trends. This may indicate that the one year wear

period did not result in sufficient wear to deteriorate the condition of the rail surface and increase noise levels.

Curved Track

In Test Series 1, wheel squeal was observed to increase after rail grinding, while in Test Series 2, decreases in wheel squeal noise were observed after rail grinding. The results of the SEPTA tests provide a basis for concluding that grinding curved rail does not produce consistent reductions of wheel squeal noise at short radius curves, regardless of wheel wear condition.

4.3.2 Generalized Rail Grinding Results

Table 4-1 presents a summary of rail grinding results from SEPTA, BART [7,12], CTA[9], and Munich[13]. The results from BART, CTA and Munich primarily consist of before and after grinding continuous welded tangent rail, although there was one test at BART on short radius subway curves. The data from all three systems include measurements on newly placed rail that had never been ground or used in service to remove the rust and mill scale, and the CTA tests included measurements on worn rail. None of the tests included noise measurements on corrugated rail.

In all of the tests, grinding the new rail created significant reductions in noise levels, the largest being the 6 to 9 dBA reduction observed at BART.

The CTA tests included four transit cars, three standard cars and one car that had the trucks modified to be more resilient by replacing the standard journal sleeves with soft journal sleeves. Replacing the journal sleeves resulted in

TABLE 4-1. SUMMARY OF RAIL GRINDING RESULTS. THE RESULTS FROM VARIOUS TESTS AT SEVERAL TRANSIT SYSTEMS ARE GIVEN SHOWING THE LEVELS WITH GROUND RAIL RELATIVE TO WORN OR NEW RAIL.

Wheel Type and Condition	Track Construction	Comparison Track	Change in Sound Level - dB	
			Wayside	Car Interior
SEPTA				
Standard	Tangent welded, ballast and tie	Worn, 1 to 2 years	0 to -1	0 to -1
Trued*		Worn, 2 years	-3 to -4	0 to -1
Resilient-New		Worn, 1 year	-1 to -2	0 to -1
Standard	Tangent jointed, ballast and tie	Worn, 1 to 2 years	0 to -4	0 to -3
Resilient			0 to -4	0 to -2
Ring-Damped			0 to -4	0 to -2
New/Trued Stnd.	Subway, welded, concrete invert	Worn, 1 year	--	0 to -2
Worn Stnd.			--	0 to -1
Resilient			--	-1 to -3
New/Trued Stnd.	Subway, jointed, concrete invert	Worn, 1 year	--	0 to -3
Worn Stnd.			--	0 to -1
Resilient			--	-1 to -3
Standard, New/Trued	Short radius curve	Worn, 1 year	+2 to -3	0 to -3
Standard, Worn			+2 to -6	-2 to -3
Ring-Damped			-2 to -3	0 to -1
BART [REF. 12]				
Standard, New	Ballast and tie, welded	New, no wear	-6 to -9	-4 to -5
BART [REF. 7]				
Standard	Short radius curve, subway	New, no wear	+9 to -6	+7 to -7
Visco-Damped			+4 to -10	+1 to -8
CTA [REF. 9]				
6000 Series Cars	Ballast and tie, welded	Worn	0 to -2	--
2200 Series			-2 to -3	--
2000 Series [Stnd.]			-2	-1 to -2
2000 Series [Modified]			-4	-2 to -3
6000 Series	Ballast and tie, welded	New, no wear	-3 to -4	--
2200 Series			-4	--
2000 Series [Stnd.]			-4	--
2000 Series [Modified]			-7	--
MUNICH [REF. 13]				
Standard	Ballast and tie in subway	New, no wear	-6	--

*This data was taken immediately after truing the wheels. The cutter marks still on the wheel treads apparently resulted in higher noise levels on most test tracks. This result was also found in Toronto [Ref. 21], where second tests after two weeks wheel wear showed noise levels were reduced to levels below that before truing, apparently due to smoothing of the cutter marks.

noise reductions as high as 6 to 8 dBA. In addition, before/after rail grinding results showed greater noise reductions with the modified cars than with the standard cars. With the standard CTA transit cars a 3 to 4 dBA noise reduction was measured after grinding the new rail; with the modified 2000 series car the reduction was 7 dBA. The reductions due to grinding the worn rails were 0 to 3 dBA for the standard cars and an average of 4 dBA with the modified car.

In conclusion, it is obvious that the amount of noise reduction that will be achieved with rail grinding is dependent on the condition of the track before grinding and on the condition of the wheels. The track at SEPTA had been in service a number of years before the start of the test program, however, it had been ground approximately one year before the testing and showed little evidence of corrugations and only limited pitting, spalling or shelling. Therefore grinding did not generally result in significant changes in wayside or car interior sound levels. The primary exception was the first grinding of the TJ test segments that resulted in 3 dBA reduction in wayside noise level and 1 to 2 dBA reduction of the car interior noise. Unfortunately, none of the tests at SEPTA, BART, TTC or CTA included noise measurements before and after grinding corrugated rails. It has often been observed that corrugated rail results in very noticeable increases in noise level, typically 5 to 10 dBA sometimes even higher, and that grinding to remove the corrugations brings the noise level back to normal.[9, 14]

4.4 WHEEL TRUING

4.4.1 SEPTA Results

The testing at SEPTA indicated measurable acoustical differences between worn wheels, new wheels and trued wheels.

New wheels delivered to SEPTA have had the tread surface smoothed and contoured with a lathe-type truing machine and SEPTA uses an underfloor milling machine type truer. The new wheels were consistently quieter than the trued wheels and the trued wheels consistently quieter than the worn wheels. The primary exception occurred after truing the wheels in Test Series 2 when the noise levels on the TJ and TW test tracks increased. This phenomenon was apparently due to the milling machine cutter marks still being on the wheel tread surface because the tests were performed before the wheels had been used in service.

For the wayside and interior noise at the TW track the new wheels averaged approximately 3 dBA quieter than the wheels worn 12 months and the trued wheels (ignoring the Test Series 2 data) averaged 0 to 2 dBA quieter. Similar results were observed at the TJ test track; however, the differences were smaller and less consistent, making it impossible to draw any definitive conclusions regarding the noise reduction achieved at the TJ test track with wheel truing.

In most cases the reductions with new and trued wheels were consistent and significant at the subway test tracks. Very similar results were observed at the welded and jointed subway test tracks. Compared to wheels worn by 12 months of service, the new wheels averaged 0 to 3 dBA less noise, the trued wheels averaged 4 to 5 dBA less noise and the wheels worn 24 months averaged 2 to 4 dBA greater noise. This is the only case where the new wheels were not as effective as the trued wheels.

Wheel truing was also found to provide 2 to 6 dBA reduction of wheel squeal noise on curves.

4.4.2 Generalized Wheel Truing Results

The wheel truing results are summarized in Table 4-2. There is not much data available on changes in noise level after wheel truing from other systems, however, there is one notable result from WMATA system measurements[14]. Wayside noise levels from WMATA trains with wheel flats were found to be 9 to 10 dBA higher than for trains with normal smooth wheels. Similar results have been observed but not documented in Toronto.

The SEPTA results show that modest noise reductions can be achieved by truing wheels without wheel flats and the WMATA data indicate that large reductions can be achieved by truing flatted wheels. It should be noted that the vibration measurements discussed in Section 5 indicated that the test wheels were creating impact noise even though the impacts were not identifiable as airborne noise. This may be an indication that the wheel truing was effective in this study because the irregularities of the wheel tread that resulted in wheel/rail impacts were removed. The irregularities can be the results of pitting, spalling or shelling of the wheel surface or can result from sliding of the wheels on the rails.

4.3 RESILIENT WHEELS

The results with resilient wheels at SEPTA and some tests at BART[7] and London Transport[5] are summarized in Table 4-3. As discussed in Section 1, only limited tests with resilient wheels were possible in this study because of the problems experienced with the resilient wheels that forced removal of the wheels at the end of Test Series 1. In all of the testing, the resilient wheels were in close to new condition.

TABLE 4-2. SUMMARY OF WHEEL TRUING RESULTS. THE RESULTS SHOWN ARE THE LEVELS WITH WHEELS IN A "TEST CONDITION" RELATIVE TO WHEELS IN A "REFERENCE CONDITION".

Track Type	Wheel Condition		Change in Sound Level - dBA	
	Test	Reference	Wayside	Car Interior
SEPTA				
Ballast & tie, welded	New	Worn, 12 Mo.	-2 to -3	0 to -5
Ballast & tie, welded	Trued*	Worn, 12 Mo.	+4 to -2	+4 to -2
Ballast & tie, welded	Worn, 12 Mo.	Worn, 24 Mo.	0	0
Ballast & tie, jointed	New	Worn, 12 Mo.	-1 to -2	0 to -3
Ballast & tie, jointed	Trued*	Worn, 12 Mo.	0 to -2	+3 to -1
Ballast & tie, jointed	Worn, 12 Mo.	Worn, 24 Mo.	0 to -1	0 to -2
Subway, welded	New	Worn, 12 Mo.	--	0 to -3
Subway, welded	Trued	Worn, 12 Mo.	--	-4 to -5
Subway, welded	Worn, 12 Mo.	Worn, 24 Mo.	--	-2 to -4
Subway, jointed	New	Worn, 12 Mo.	--	0 to -3
Subway, jointed	Trued	Worn, 12 Mo.	--	-4 to -5
Subway, jointed	Worn, 12 Mo.	Worn, 24 Mo.	--	-2 to -4
Curve	New	Worn, 12 Mo.	-4 to -5	-3 to -4
Curve	Trued	Worn, 12 Mo.	-2 to -5	-2 to -6
Curve	Worn, 12 Mo.	Worn, 24 Mo.	0	0
WMATA [REF. 14]				
Ballast & tie, welded	Flatted	Smooth	+9 to +10	--
NYCTA [REF. 15]				
Ballast & tie, welded	Smooth	Worn, 3-8 Mo.	-5 to -8	--

*Wheels were tested immediately after truing. The noise levels were higher than before truing apparently because the cutter marks had not been smoothed off.

TABLE 4-3. SUMMARY OF EFFECTIVENESS OF RESILIENT WHEELS. THE TABLE SHOWS THE LEVELS WITH RESILIENT WHEELS RELATIVE TO LEVELS WITH SMOOTH STANDARD WHEELS.

Track Type	Wheel Type	Relative Noise Level - dBA		Relative Noise Level at Squeal Frequencies, dB
		Wayside	Car Interior	
SEPTA				
all tangent track, welded and jointed	Acousta Flex	0 to -1	0 to -2	--
	Penn Bochum	0 to -1	0 to -2	--
	SAB	0 to -1	0 to -2	--
Curve	Acousta Flex	-8 to -10	-1 to -2	-5 to -30
	Penn Bochum	-8 to -10	-1 to -2	-20 to -30
	SAB	-3 to -4	0 to -1	0 to -30
BART [REF. 7]				
Ballast & tie, welded	Acousta Flex	0 to -2	0 to -2	--
	Penn Bochum	0 to -2	0 to -2	--
Subway, curve	Acousta Flex	-3 to -9	-1 to -5	-3 to -25
	Penn Bochum	-9 to -16	-8 to -18	-15 to -30
LONDON TRANSPORT [REF. 16]				
Tunnel	Penn Bochum	--	-4.6	--
	SAB	--	-3	--

The results with resilient wheels at SEPTA are quite consistent with those from the BART tests. The maximum noise reduction on tangent track was 2 dBA while on curved track the wheel squeal reduction was very dramatic. The Acousta Flex and Penn Bochum wheels virtually eliminated the wheel squeal. At SEPTA the reduction of overall noise level was 8 to 10 dBA at the wayside and 1 to 2 dBA in the car interior. The A-weighted sound levels do not accurately reflect the subjective effectiveness of the resilient wheels; at the squeal frequencies the noise reduction with the resilient wheels was as high as 30 dB, both at the wayside and in the car interior. Because of the shape of the noise spectra in the car interior this large reduction of wheel squeal noise does not have a strong influence on the overall A-weighted noise levels, however, the reduction of the pure tone screech noise substantially reduces the irritating or annoying quality of the noise.

Although the SAB wheels created considerably less squeal noise than the standard wheels, they were substantially less effective than the other resilient wheels at controlling wheel squeal noise. Based on loss factor tests, this is not a surprising result. The SAB wheels have considerably higher internal damping than the standard, undamped wheels; however, above 2000 Hz the loss factors of the Acousta Flex and Penn Bochum wheels are approximately 8 to 10 times greater than those of the SAB wheels.

In summary, acoustical results of the tests of resilient wheels indicate that the resilient wheels provide at best a small reduction of roar and impact noise on tangent track but are very effective at reducing wheel squeal noise on curved track. In some cases the wheel squeal noise is completely removed.

4.6 DAMPED WHEELS

The test program at SEPTA originally included visco-elastic damped wheels. As discussed in Section 1 these wheels were not included in the program because SEPTA personnel had questions regarding their safety.* However, in Test Series 2 two sets of ring-damped wheels were included in the test program.

Basically the SEPTA tests did not indicate any measurable reduction of noise on tangent track using ring-damped wheels. However, the ring-dampers did result in dramatic reductions of wheel squeal noise on the curve test track. This is consistent with the measurements of damping loss factors. The ring-dampers were found to provide significant damping above approximately 1400 Hz (approximately equal to the loss factors of SAB wheels). Below 1400 Hz the loss factors were the same for damped and undamped wheels.

Because of the success of the ring-damped wheels at controlling wheel squeal as observed during the Phase IV, V and VI tests, the Phase VII tests were scheduled to further investigate ring-damped wheels on curved track. A set of wheels grooved on both the field side and the flange side was mounted on Car 606. In Phase VII, four tests were performed at the TURN test track with Car 606 - rings out, rings in both sides, rings in the field side only, and rings in the flange side only. The results from these tests do not indicate any identifiable acoustical differences between the three ring configurations.

The original ring-damped wheels on Cars 607/644 were also tested in Phase VII. At the time of the Phase VII tests the wheels had been in normal revenue service for just over 10

---

* Note that in-service tests that were performed with visco-elastic dampers at BART did not encounter any safety related problems. In fact it was impossible to remove the dampers from the wheels after the testing without destroying the dampers.

months. The original test plan included tests with Cars 607/644 with the rings in and the rings out. However, in the first tests with Cars 607/644 with the rings in, a significant amount of squeal was observed. Subsequently, the rings were found to be very rigidly frozen into the grooves and extremely difficult to remove from the grooves. It was necessary to destroy several rings in order to remove them from the grooves. Because of the poor performance of the ring dampers when frozen in place, an extra set of tests was performed with Cars 607/644 with new ring-dampers installed in the grooves. The new ring-dampers virtually eliminated the squeal noise and returned the noise to conditions similar to those when the original rings were first installed.

The test results clearly indicate that when the ring-dampers freeze into the grooves due to corrosion or other mechanisms, such as brake dust, the rings no longer provide sufficient damping to control wheel squeal. This is a very important result, strongly indicating that ring-dampers should not be retrofitted on transit vehicle fleets until more is known about the mechanism causing the bonding and a satisfactory method of maintaining the rings free in the groove has been developed. Note that ring-dampers have been installed on several of the new 2400 series CTA cars. The CTA experience is that the rings remain free in the grooves after more than a year of revenue service. Another example is the London Transport System where ring-dampers have been in routine use since 1938 without experiencing problems with the rings binding in the grooves.

Table 4-4 presents a summary of the results with ring-dampers at SEPTA,CTA[17,18] and London Transport[19], and the results with visco-elastic rings at BART[7]. The results are quite consistent; little or no reduction of noise on tangent

TABLE 4-4. SUMMARY OF EFFECTIVENESS OF DAMPED WHEELS. THE TABLE SHOWS THE LEVELS WITH DAMPED WHEELS RELATIVE TO LEVELS WITH SMOOTH STANDARD WHEELS.

Track Type	Wheel Type	Relative Noise Level - dBA		Relative Noise Level at Squeal Frequencies, dB
		Wayside	Car Interior	
SEPTA				
All tangent, track, welded and jointed	Ring-damped	0 to -1	0 to -1	--
Curve	Ring-damped, rings new	-2 to -11	-2 to -3	-10 to -25
Curve	Ring-damped, rings frozen	0 to -5	--	0 to -5
CTA [REF. 17]				
Tangent track, jointed	Ring-damped	-1 to -2	0 to -1	--
Tangent track, welded	Ring-damped	0	0	--
Curve	Ring-damped	-3 to -8	-5 to -9	-5 to -20
CTA [REF. 18]				
Tangent track, welded	Ring-damped	-2	--	--
Curve	Ring-damped	--	0 to -9	-1 to -15
BART [REF. 7]				
Ballast and tie, tangent, welded	Visco-elastic damped	0	0	--
Subway, curve	Visco-elastic damped	-5 to -10	0 to -2	0 to -25
LONDON TRANSPORT [REF. 16]				
Tangent	Ring-damped	0	0	--

track was observed but large reductions of wheel squeal noise were observed.

As discussed above, the ring-dampers do not create significant damping below 1400 Hz. Since wheel squeal at SEPTA generally consists of components above 2000 Hz; non-bonded ring-dampers are very effective at controlling wheel squeal. However, many transit systems including BART and CTA [with aluminum center wheels] have significant squeal noise below 2000 Hz. The visco-elastic rings tested at BART were effective at controlling the squeal noise below 2000 Hz, however, the ring-dampers at CTA were only marginally effective at controlling squeal noise below 2000 Hz. In many of the CTA tests a squeal component in the 1600 Hz 1/3 octave had essentially the same level with and without the ring-dampers. This leads to the conclusion that ring-dampers of the design used in this study will not adequately control squeal noise below about 2000 Hz.

The field measurement program of this project did not allow for a thorough investigation of the vibration properties of the ring-damped wheels. It is evident that ring-dampers need to be studied more thoroughly before an optimum design can be developed. The most advanced studies performed to date [to the authors' knowledge] have been sponsored by the Ontario Ministry of Transportation and Communications. Their studies have included investigation of the vibration properties of resilient and ring-damped wheels under well controlled laboratory conditions. In their most recent report, "Vibration Properties of Two Ring Damped TTC Wheels",[19] the natural frequencies and modal damping of ring-damped wheels were investigated. The tests showed a significant difference in the damping effects when the ring-dampers were installed on the two

wheels. It is as yet unknown whether the differences resulted from differences in the wheels (one was worn and one was new) or differences in the manner in which the ring fit in the groove. Further studies to investigate the effects on damping of ring tension, clearance between the ring and the groove, and the ratio of ring and rim mass have been proposed.

4.7 JOINTED VS. WELDED RAILS

Although the primary purpose of this study has been to evaluate the noise reduction potential of rail grinding, wheel truing, resilient wheels and damped wheels (because the testing was performed on a number of different types of track construction), comparisons can also be made of noise levels on welded and jointed rails. Switching from jointed to welded rails is an expensive, but very effective method of reducing the patron and community impacts of wheel/rail noise. Not only is the sound level reduced with welded rail, but the absence of joint impact noise changes the character of the noise. Noise without rattles, impacts, clicks, etc., is considerably less annoying and intrusive than noise at the same level that contains identifiable components such as repetitive impacts or rattles. Unfortunately, acoustical instrumentation cannot measure the increase in annoyance caused by rattles or impacts. Typically noise ordinances and specifications account for this by including a 5 dB penalty when the noise contains identifiable impacts, pure tones, etc.

Figure 4-7 presents a set of comparisons of the wayside levels at the TJ (jointed) and TW (welded) SEPTA test track sections. The comparisons include the best fit lines for worn wheels on worn rails and new wheels on ground rails. Although the quietest condition on the jointed rail is only about 2 dBA

above the highest noise level condition on the welded rail, the average difference of the data in Figure 4-7 is 6.5 dBA. Taking into account all of the SEPTA test data on the TJ and TW tracks, the noise levels on the jointed track average 4 dBA higher at the wayside and 2 dBA higher in the car interior than on the welded track. Note that the noise levels on welded rail, especially in Test Series 2 are apparently limited by the levels of propulsion equipment noise. It is anticipated that without the propulsion equipment noise the difference between welded and jointed rail would be greater.

Figure 4-8 presents a comparison of the results at the subway test tracks with jointed and welded rail. In Test Series 1 a small difference of 1 to 2 dBA was observed; this difference was independent of speed. Although the difference in A-weighted level is relatively small, the difference between jointed and welded track was clearly audible. However, in Test Series 2 the car interior sound levels on the jointed and welded subway test tracks were indistinguishable above speeds of approximately 50 km/hr. This was noticed during the testing, the individual joint impacts could not be discerned indicating that the joints were in very good alignment during these tests.

The SEPTA results on jointed and welded rail are similar to test results on other transit systems. Tests at CTA[9] showed a 5 to 8 dBA reduction of wayside noise when comparing welded rail to jointed rail (ballast and tie trackbed). The corresponding reduction of the car interior noise was 0 to 4 dBA. A recent study at NYCTA[20] included comparisons of car interior noise in stations with jointed and welded rail. This study found a reduction of only 1.5 dBA, apparently because the propulsion system noise was greater than the wheel/rail noise.

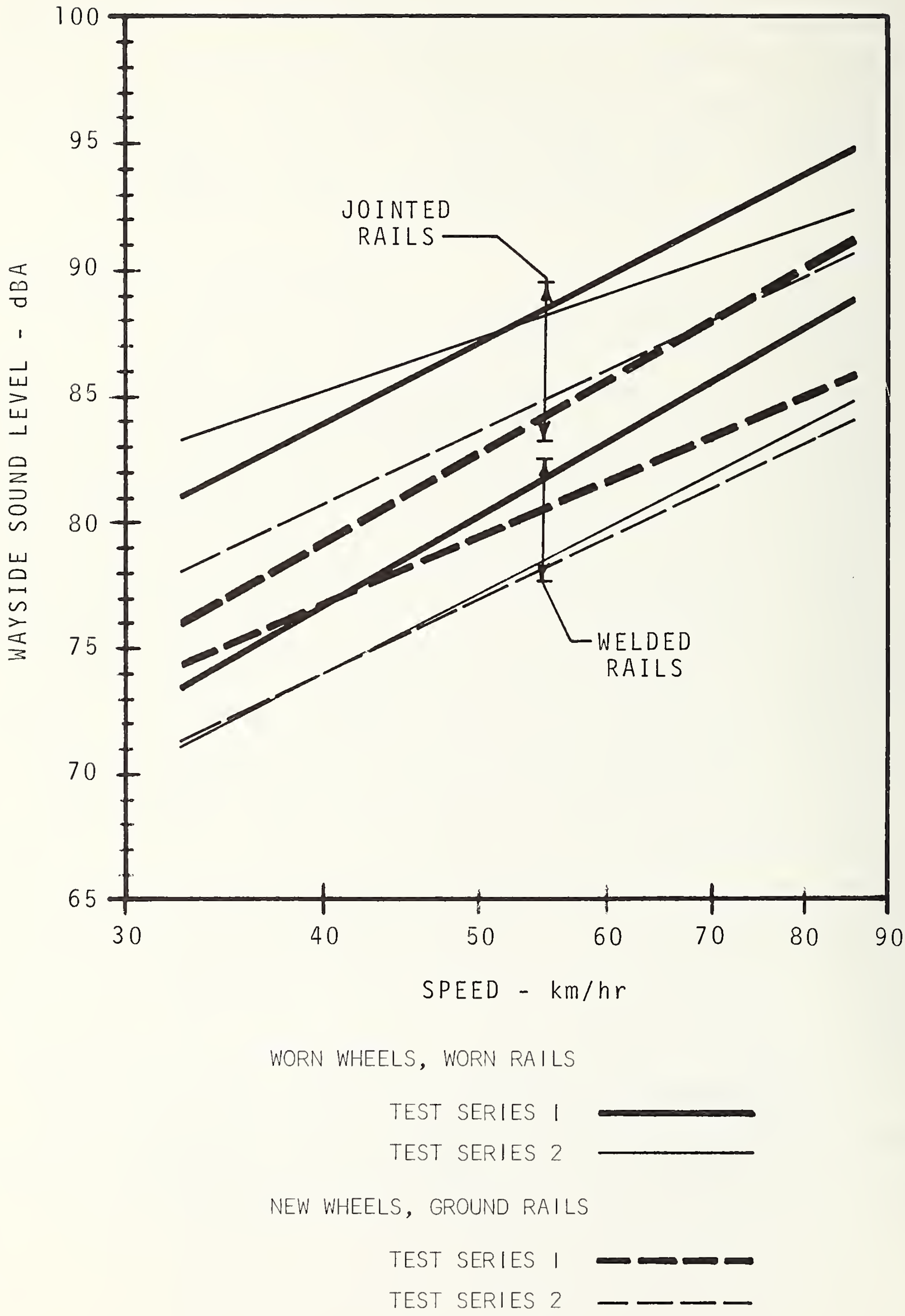


FIGURE 4-7. COMPARISON OF WAYSIDE LEVELS ON TANGENT JOINTED AND WELDED RAILS, B & T TRACKBED 7.5 m FROM TRACK CENTERLINE

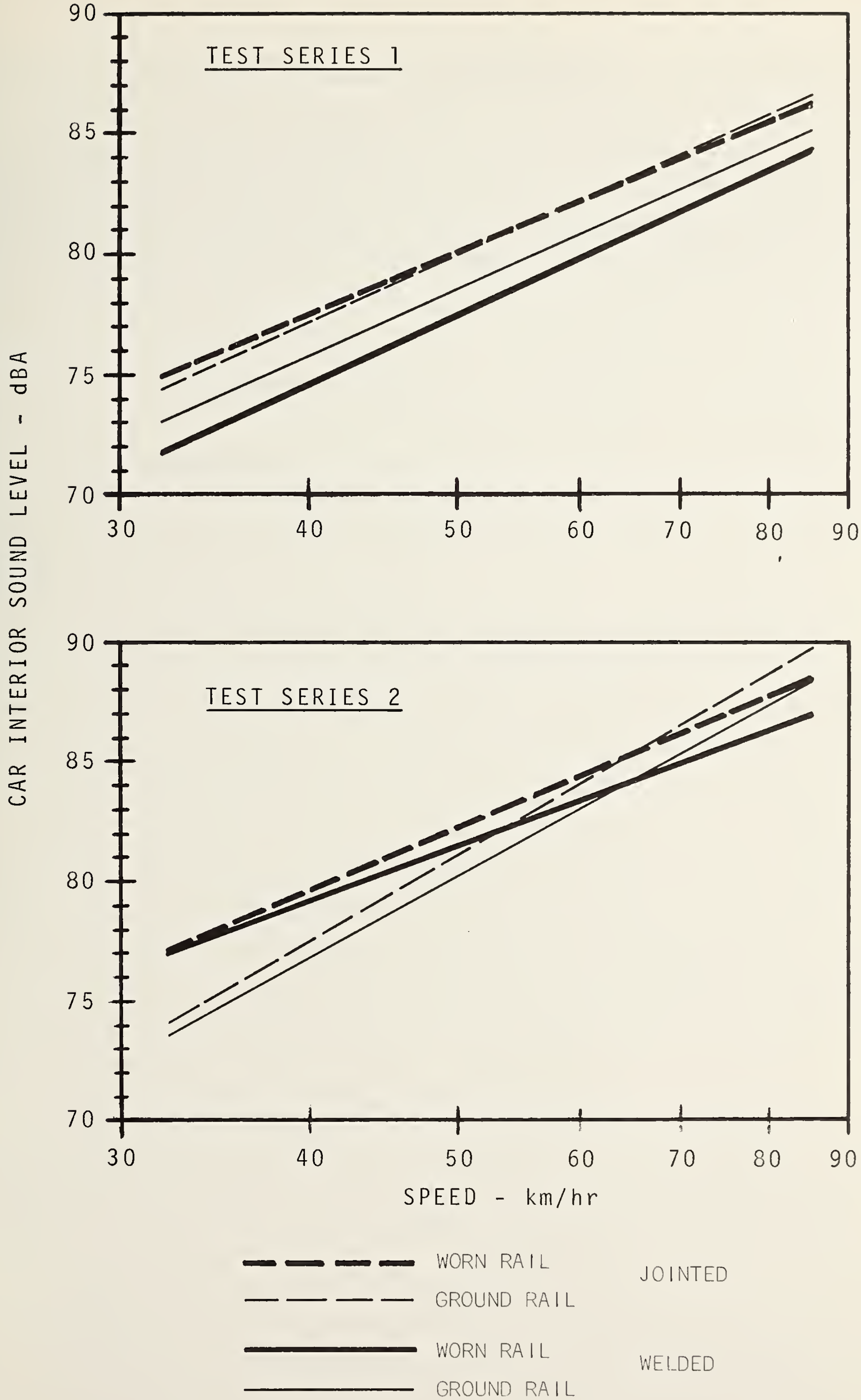


FIGURE 4-8. COMPARISON OF CAR INTERIOR LEVELS ON JOINTED AND WELDED RAILS, SUBWAY TEST TRACKS

The general conclusion drawn from the comparison of noise on jointed and welded rail is that use of welded rail will result in significant acoustic benefit to both the transit patrons and the wayside community. Although the measured noise reduction may be small in certain circumstances, removing the joint impact noise substantially reduces the subjective loudness of the train noise.

5. GROUND-BORNE VIBRATION

At many transit systems the structure-borne vibration created at the wheel/rail interface results in noise and vibration intrusion inside adjacent structures. The vibration produced at the wheel/rail interface by the wheels rolling on the rails is transmitted from the transit structure through the ground to nearby structures. The vibration of the building structure is sometimes perceptible as mechanical motion but more often appears as a low frequency rumbling noise radiated from the room surfaces inside buildings, i.e., as structure-borne noise. In some cases the building vibration will also result in secondary noise radiation due to rattling of dishes on shelves, etc.

In areas where ground-borne vibration and noise may result in intrusion, special design features can be incorporated into the transit structures and rolling stock to reduce the levels of vibration. However, on existing facilities there are relatively few practical methods for reducing vibration.

Control of ground-borne noise and vibration is a major concern of both new and existing rail transit systems. Since methods that reduce wheel/rail noise should also reduce the vibration transmitted from the wheel/rail interface, the field tests included in this study represented a unique opportunity to evaluate the effectiveness of the noise control methods at reducing ground-borne noise and vibration.

During several of the Phase I and Phase II acoustical tests, measurements were also performed of rail, structure and ground-borne vibrations. The vibration measurements were performed by personnel of the Port Authority of New York and

New Jersey using specialized instrumentation that has been developed by WIA for efficient measurement of low level, low frequency vibrations. The results of the vibration tests were presented in Interim Report #4. The purpose of this section is to present the overall results of the SEPTA vibration measurements and to compare these results with measurements that have been performed at other transit systems. The SEPTA results were compared to results from the TTC[21,22] (Toronto), WMATA Metro[23] (Washington, D.C.), MARTA[24] (Atlanta) and BART[25,26] (San Francisco) transit systems.

All of the vibration measurements at the SEPTA facilities were performed at welded rail sections of the subway and elevated structure. In the subway the rails are rigidly attached to wood ties imbedded in the concrete invert. Measurements at the subway location included: rail vertical vibration, invert vertical and lateral vibration and vertical vibration of the floor in the basement of a building adjacent to the subway structure. The accelerometer on the basement floor was located approximately 14 m from the centerline of the test track.

The SEPTA elevated structure is a relatively heavy structure consisting of a concrete deck with ballast and tie trackbed. At the elevated structure, measurements were made of structure vertical vibration at the edge of the concrete deck and rail vertical vibration.

The SEPTA tests included five 2-car test trains with worn standard wheels, trued standard wheels, Acousta Flex resilient wheels, Penn Bochum resilient wheels and SAB resilient wheels. At the subway test track, measurements were performed with the three sets of resilient wheels both before and after rail grinding.

5.1 COMPARISON OF VIBRATION LEVELS

Figures 5-1 through 5-3 present examples of the 1/3 octave band spectra of ground-borne vibration for various test conditions. Figure 5-1 presents data on the vertical vibration levels at the subway inverts of four transit systems for similar operating conditions. At the measurement locations the subway structures are all cut and cover box type structures except at TTC where it is a concrete lined circular earth tunnel. All the measurements were on the side bench or directly on the invert approximately 0.2 m outboard of the rails. The rails for the SEPTA, TTC and WMATA tests were all in relatively smooth condition and for the MARTA tests the rails had been recently installed and had not been ground. TTC, WMATA and MARTA have resilient direct fixation rail fasteners of similar design and the SEPTA rails are rigidly attached to the invert via cast-in-place wood ties.

The rigid attachment of the SEPTA rail is reflected in the vibration levels above 125 Hz being significantly higher than at the other systems. The spectra presented in Figure 5-1 show that the invert vibration has the same general shape over most of the frequency range in spite of the large variations in subway structure, rolling stock and track fixation. The significant variations are the higher vibration levels below 16 Hz at SEPTA; the relatively low levels at WMATA above 140 Hz; and the strong peaks in the WMATA and MARTA spectra at 20 and 25 Hz respectively. The results of a recent study at CTA[26] showing ground vibration to be strongly influenced by the truck design, indicate that these peaks may be due to the natural frequency of the trucks used on the WMATA and MARTA vehicles.

Figures 5-2 and 5-3 present average spectra for invert vertical and basement vertical vibration at SEPTA with the five test trains. All of the data have been normalized to 60 km/hr.

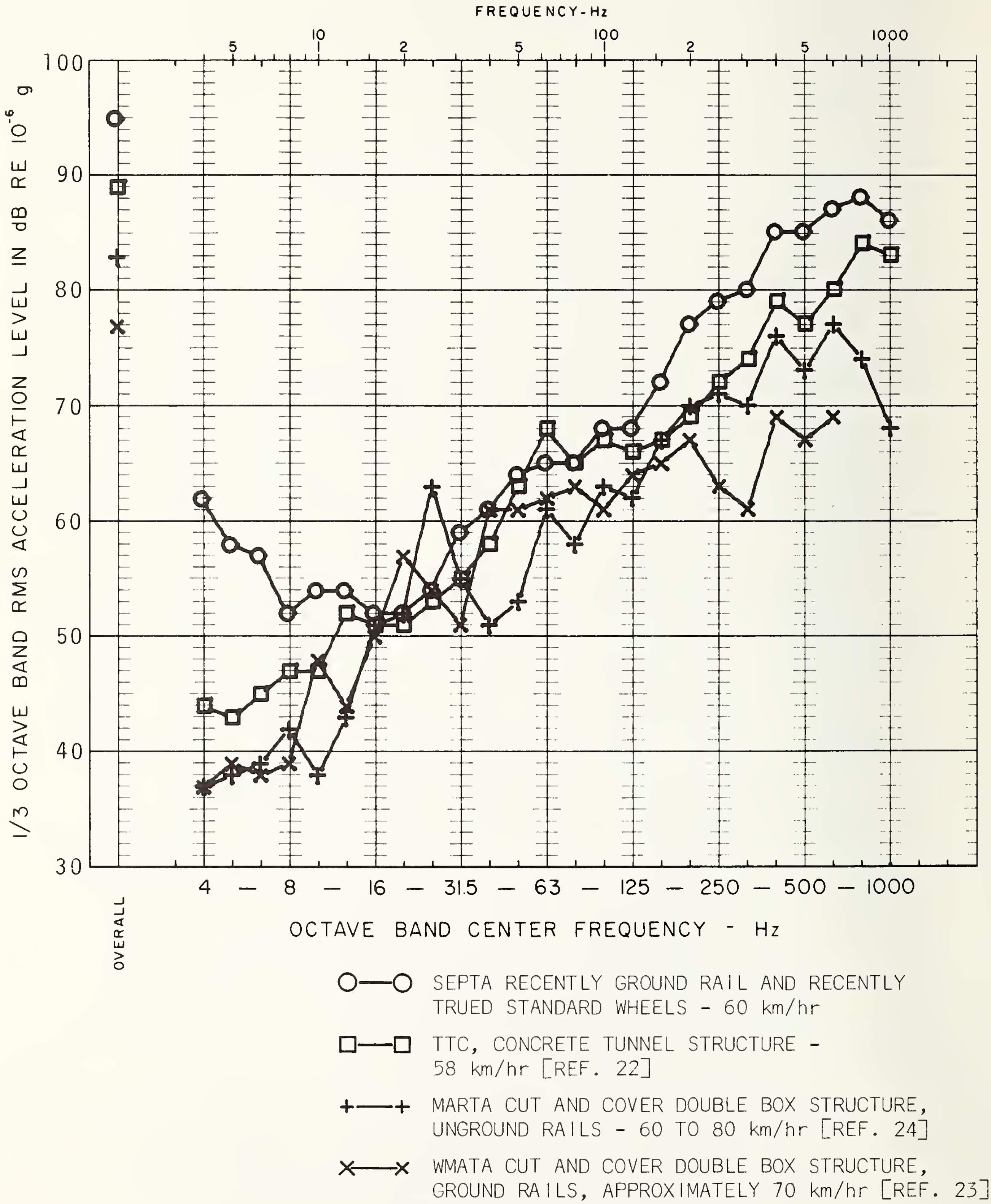


FIGURE 5-1. INVERT VERTICAL VIBRATION AT FOUR TRANSIT SYSTEMS. ALL TESTS WERE ON TANGENT WELDED RAILS WITH STANDARD STEEL WHEELS

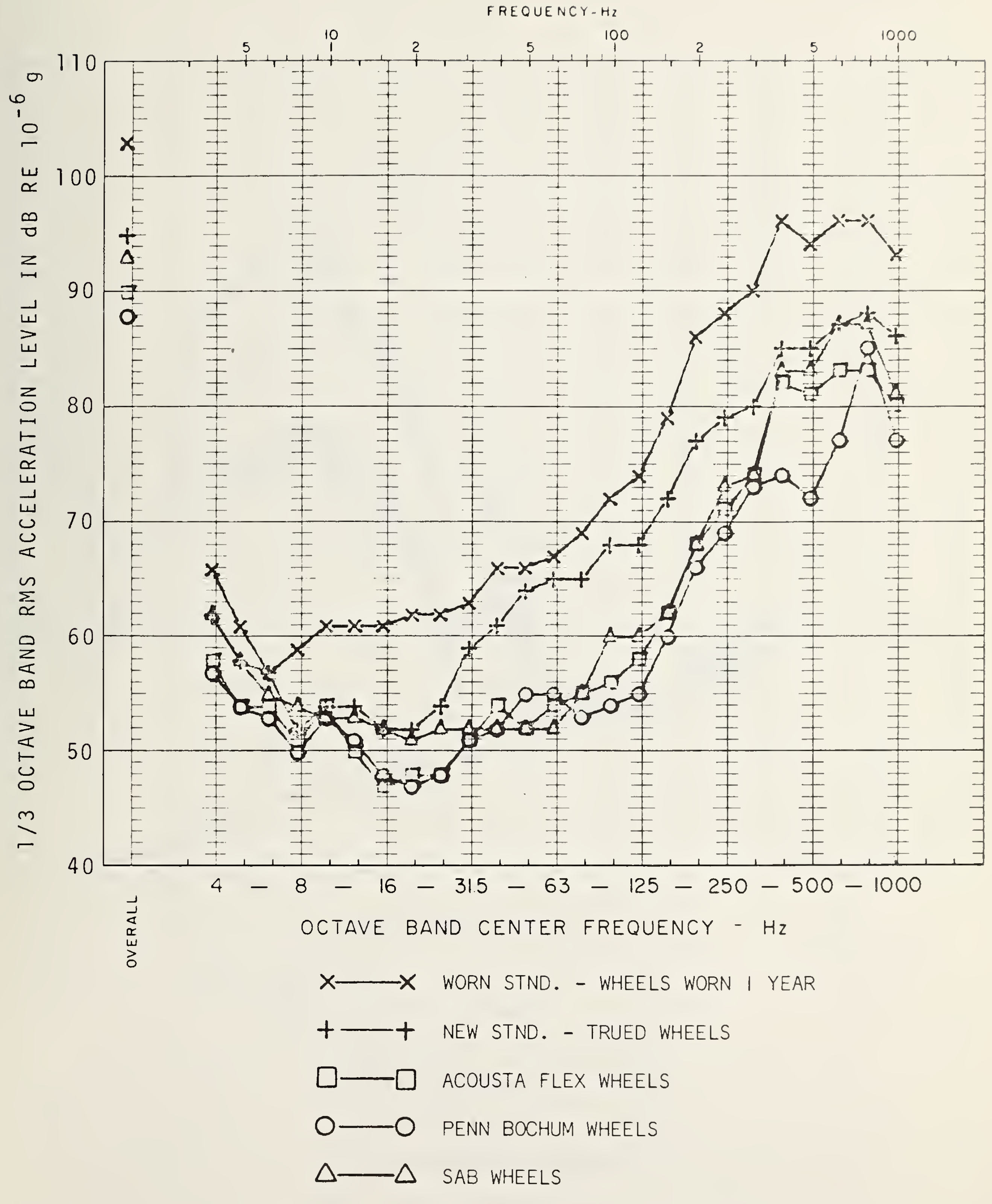


FIGURE 5-2. AVERAGE VERTICAL VIBRATION SPECTRA AT INVERT - SUBWAY TEST TRACK, TANGENT WELDED RAILS

PHASE IIB - GROUND RAILS

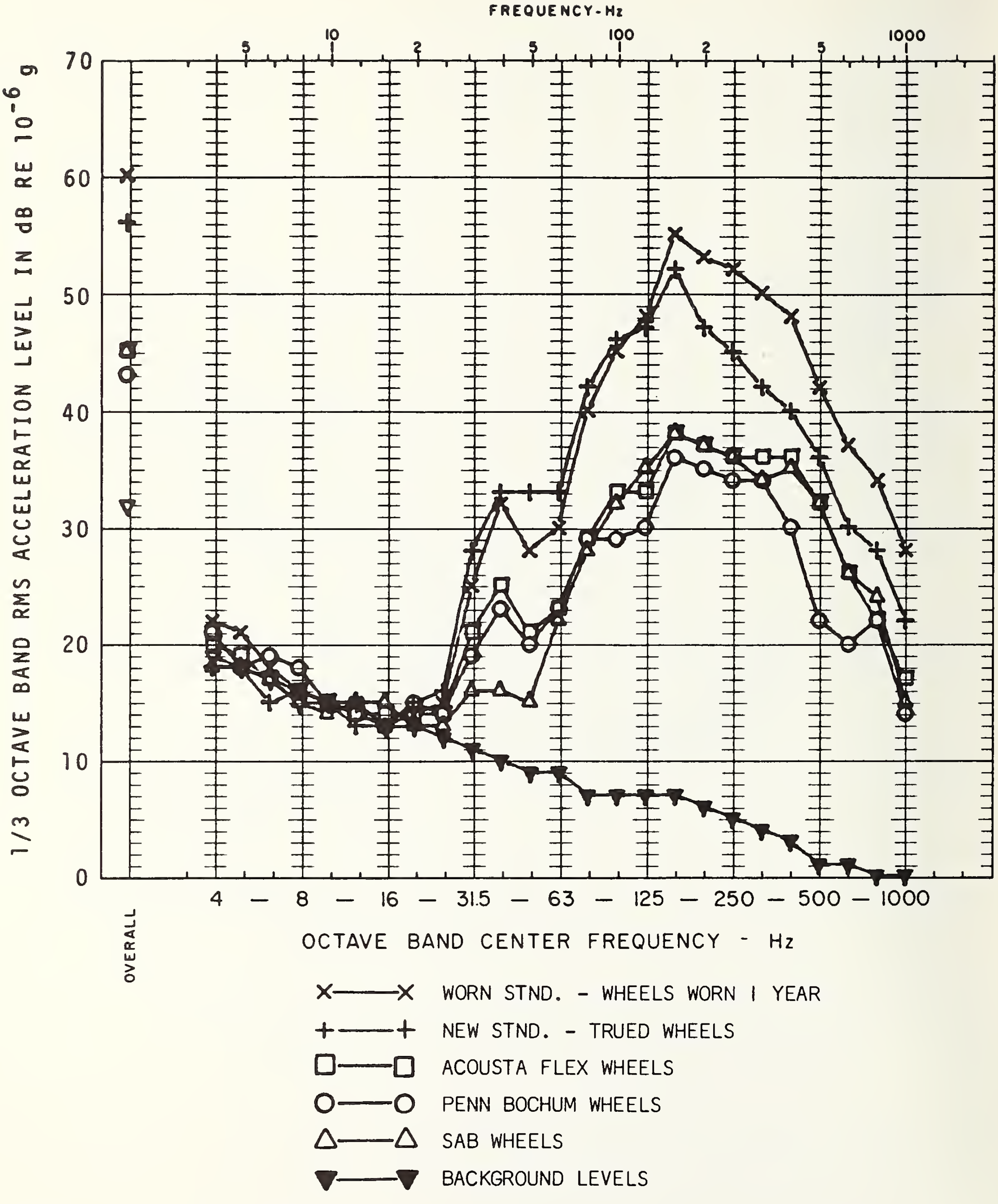


FIGURE 5-3. AVERAGE VERTICAL VIBRATION SPECTRA AT BASEMENT LOCATION - SUBWAY TEST TRACK, TANGENT WELDED RAIL

PHASE IIB - GROUND RAILS

The vibration levels with the worn standard wheels are significantly higher than any of the other test trains. This is clearly a result of the worn condition of the wheels. A factor that contributed to the relatively high vibration levels observed with the worn steel wheels was discontinuities on the wheel surface that created impacts with each rotation of the wheels. Discontinuities were not clearly identifiable on the wheel surfaces, however the impacts could have been caused by shelling or spalling of the wheel running surface or by wheel flats that had worn down. Although the noise from the impacts did not create noticeable airborne noise, the presence of the impacts was clearly evident in most of the recorded vibration signals with the worn steel wheels. To a lesser degree, some impact noise was evident in the vibration signal but not the noise for several of the tests with trued standard wheels.

The vibration spectra for the resilient wheels tended to be closely clustered at all of the test locations. There were only two regions where the resilient wheel results show consistent differences. The first is between 31.5 Hz and 63 Hz where the vibration levels with SAB wheels are several dB lower than with the Acousta Flex and Penn Bochum Wheels. This variation is evident in Figure 5-3 but not in Figure 5-2. The largest difference observed was 12 dB in the 63 Hz 1/3 octave band for the vertical vibration of the elevated structure. The consistently lower vibration levels between 31.5 and 63 Hz with the SAB wheels is due to the greater resilience of the SAB wheels compared to the Acousta Flex and Penn Bochum wheels (or compared to standard wheels) and has been observed for similar tests at other transit systems (see Reference 25).

The second significant area of difference between the resilient wheels is the dip in vibration level in the 500 Hz range exhibited by the Penn Bochum wheels. The dip occurred at all of the test conditions and typically resulted in the vibration level for the Penn Bochum wheels being 5 to 10 dB lower than for the other resilient wheels in the 500 Hz

frequency range. Since transit system vibration problems generally occur at frequencies well below 500 Hz, a reduction in vibration level around 500 Hz will not provide significant benefits for ground-borne vibration but may indicate benefit for airborne noise from wheel/rail vibration.

5.2 VIBRATION REDUCTION WITH RESILIENT WHEELS

Figure 5-4 presents the vibration reduction observed with resilient wheels at SEPTA, TTC and BART. The comparisons are of resilient wheels and standard wheels with similar amounts of wear. The SEPTA results are the average levels with the resilient wheels relative to the results with the trued standard wheels.

All of the SEPTA tests show significant vibration reduction above 20 Hz with the use of resilient wheels. Unfortunately, as discussed earlier, several of the tests with the trued standard wheels had wheel flat noise; the degree to which the wheel flats influenced the results cannot be determined.

The TTC subway data shows vibration reduction above 40 Hz with the use of Penn Bochum wheels and the BART aerial structure data shows substantial vibration reduction with SAB wheels between 16 Hz and about 100 Hz. The BART data also indicates that the SAB wheels resulted in a 3 to 4 dB increase in the vibration level above 125 Hz. This is an unexpected result; however, as discussed in Reference 25, the same 3 to 4 dB increase was found in both the vibration and the noise tests with SAB wheels. This result was not observed in the tests with the SAB wheels in this study.

The basic conclusion that can be drawn from the SEPTA test results given in Figure 5-4 is that the use of resilient wheels results in substantial reduction of ground-borne vibration and noise for frequencies above 20 Hz and has essentially no effect

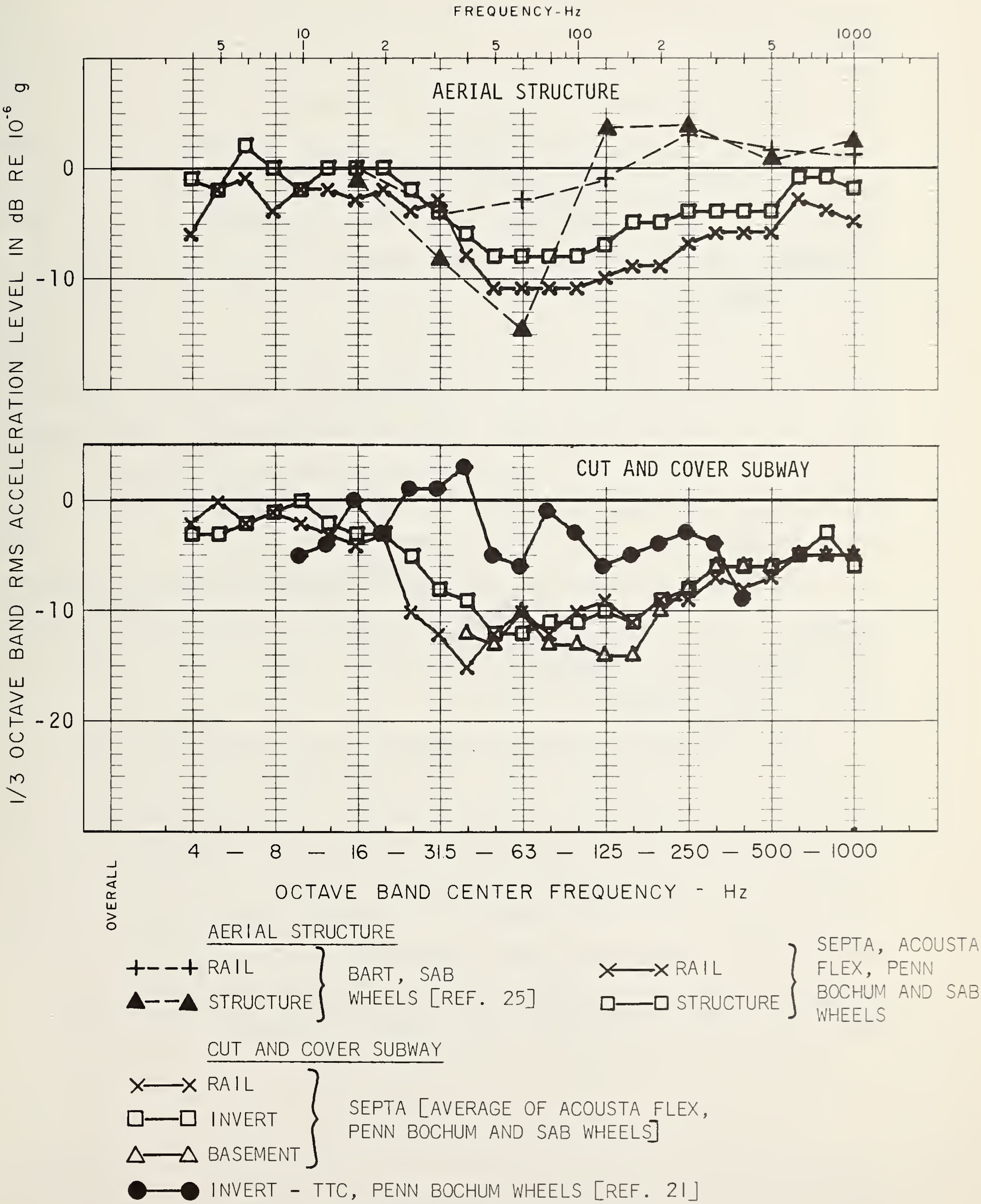


FIGURE 5-4. VERTICAL VIBRATION SPECTRA FOR RESILIENT WHEELS RELATIVE TO STANDARD WHEELS - TANGENT WELDED RAILS

below 20 Hz. Tests at other transit systems show similar trends but for different frequency ranges, thus the results can not be generalized.

5.3 VIBRATION REDUCTION WITH WHEEL TRUING

Figures 5-5 and 5-6 present the trued standard wheels and resilient wheels compared to the worn standard wheels for the SEPTA tests and one TTC test. Above approximately 100 Hz the vibration levels with the trued standard wheels are significantly lower than with the worn standard wheels for the SEPTA tests. In contrast, between approximately 31.5 and 63 Hz, the trued standard wheels created higher vibration levels than the worn wheels at several of the measurement locations. These higher levels may have been caused by differences in the wheel condition; however, it is likely that they are a result of differences in the resilience of the truck axle to frame supports or journal bearing sleeves.

The comparison before and after truing TTC wheels shows no significant change in vibration level. Unfortunately, for the series of tests reported, the wheels were in relatively good condition before truing.

The difference between the worn and trued SEPTA wheels above 125 Hz is largely due to the presence of wheel flats and other major defects on the worn wheels. It has long been known that removing wheel flats is a very important first step in controlling ground-borne vibration and noise. Since the wheel flat impacts are sometimes not an audible component of the airborne noise, and because the flats are often difficult to visually identify on the wheel surface, it can be difficult to determine when the wheels have irregularities in the wheel

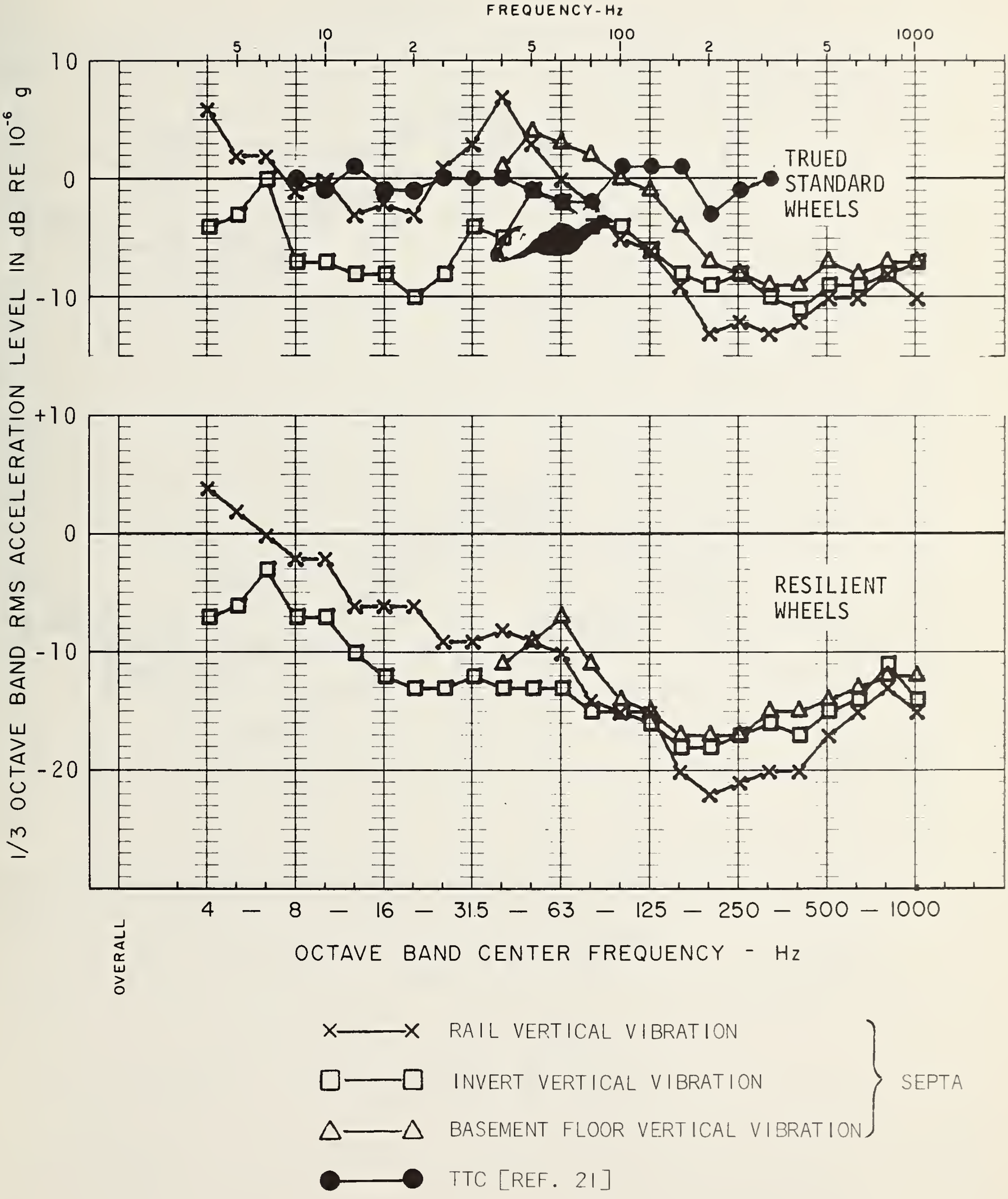


FIGURE 5-5. AVERAGE VIBRATION SPECTRA FOR NEW RESILIENT WHEELS AND TRUED STANDARD WHEELS RELATIVE TO WORN STANDARD WHEELS - SUBWAY TEST TRACK, GROUND WELDED RAILS

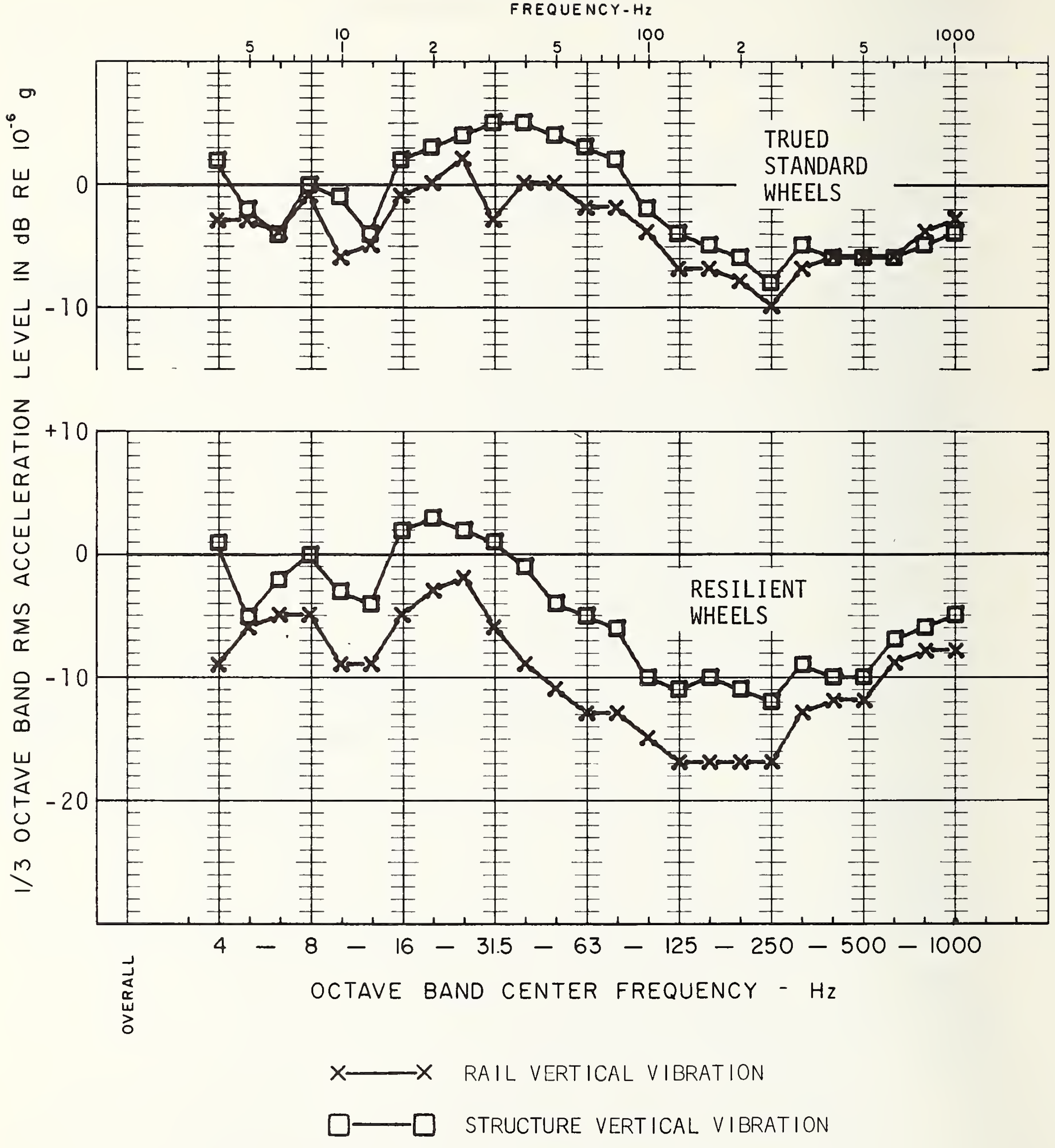


FIGURE 5-6. AVERAGE VIBRATION SPECTRA FOR NEW RESILIENT AND TRUED STANDARD WHEELS RELATIVE TO WORN STANDARD WHEELS - TW TEST TRACK, GROUND RAILS, SEPTA

contour sufficient to increase the vibration levels. It should be noted that TTC has developed a wheel flat monitoring system that automatically detects the presence of wheel flats which produce ground-borne vibration by monitoring the invert vibration levels during train passbys.[27]

5.3 VIBRATION REDUCTION WITH RAIL GRINDING

Figure 5-7 presents the results from before and after rail grinding tests at SEPTA, TTC and BART. The SEPTA results show a significant reduction of adjacent building basement floor and invert vibration above about 40 Hz. However, no significant changes in rail vibration were observed. The TTC results show a consistent 1 to 2 dB decrease in vibration level after rail grinding, a marginal improvement. However, TTC rail is generally in good condition before grinding with little evidence of corrugations.

The BART results show the most dramatic reduction after rail grinding. These tests were performed with newly placed rail that was not worn by service and that still had mill scale and other manufacturing roughness. After grinding, a consistent 6 to 10 dB reduction in vibration level was observed over the frequency range of 8 to 1000 Hz.

The test results shown in Figure 5-7 are a clear indication of the importance of regular rail grinding for control of ground-borne vibration and noise. Rail roughness can result in up to 10 dB increase in overall ground-borne noise and vibration levels, particularly if corrugations form on the rails.

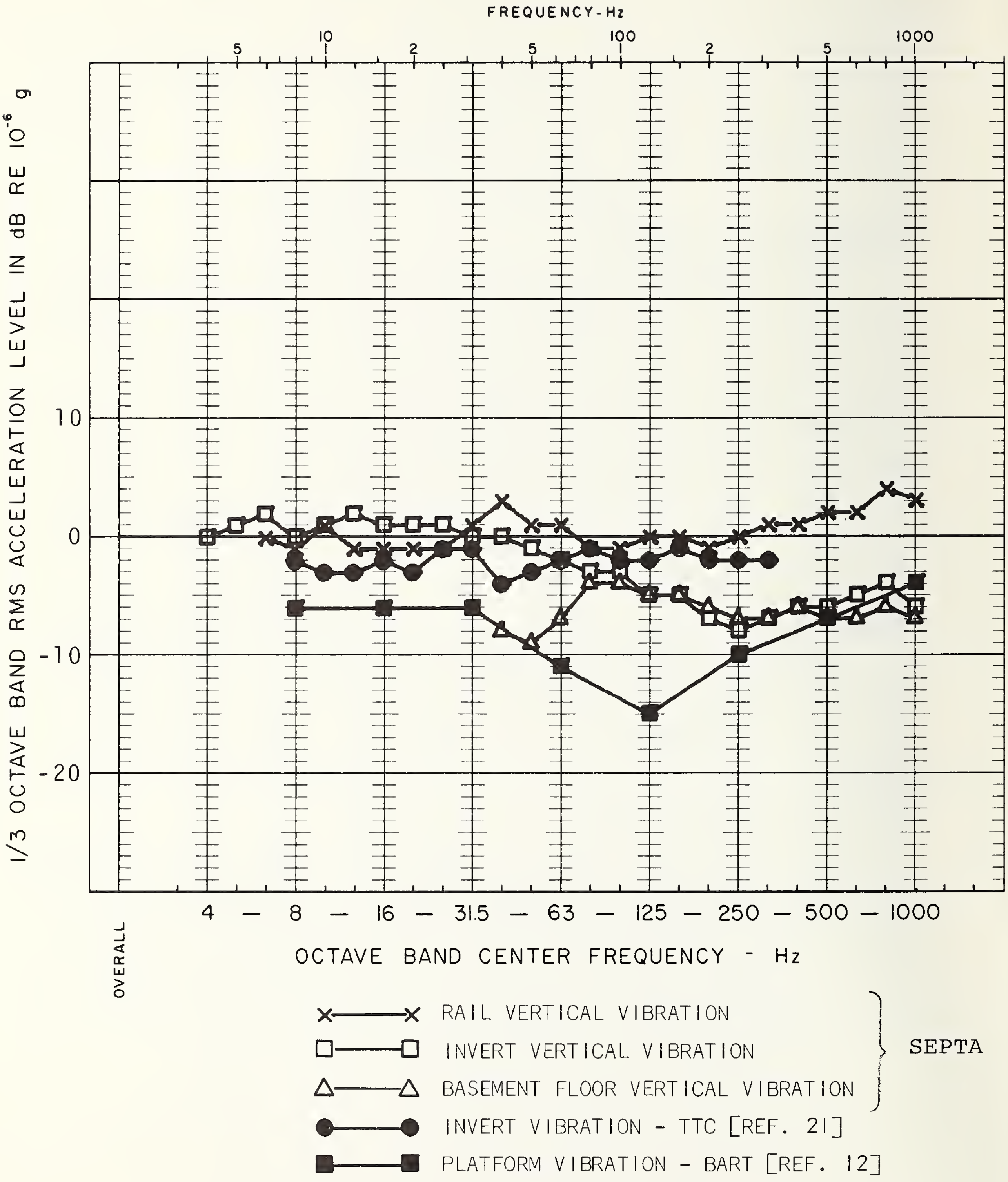


FIGURE 5-7. SPECTRA OF VERTICAL VIBRATION LEVELS AFTER RAIL GRINDING COMPARED TO BEFORE RAIL GRINDING

TANGENT WELDED RAIL IN SUBWAY

6. ECONOMIC ANALYSIS

6.1 SURVEYS OF TRANSIT SYSTEMS AND MANUFACTURERS

North American Rapid Transit Authorities were solicited concerning their past experience with noise abatement techniques and to determine their capital, operating and maintenance expenditures for wheel truing and rail grinding programs.

Wheel and equipment manufacturers were also contacted to determine capital and life-cycle costs and the life expectancy for resilient and standard steel wheels and the equipment used in the wheel truing and rail grinding process.

Transit system information was obtained by a combination of detailed questionnaires and on-site interviews with engineering, operating and maintenance personnel. The following systems participated in the survey:

Bay Area Rapid Transit (BART)
Chicago Transit Authority (CTA)
Greater Cleveland Regional Transit Authority (GCRTA)
Massachusetts Bay Transportation Authority (MBTA)
New York City Transit Authority (NYCTA)
Port Authority Transit Corporation (PATCO)
Port Authority Trans Hudson Corporation (PATH)
Southeastern Pennsylvania Transportation Authority (SEPTA)
Toronto Transit Commission (TTC)
Washington Metropolitan Area Transit Authority (WMATA)

Information was obtained from manufacturers by correspondence and telephone.

Details of the key data collected from the manufacturers and the transit authorities; along with descriptions of the transit systems, their experiences with resilient wheels, damped wheels, wheel truing and rail grinding; and detailed descriptions of the methods, procedures, manpower requirements and costs for performing wheel changing, wheel truing and rail grinding are presented in Report No. UMTA-MA-06-0025-78-7, Initial Test Series Report[3].

6.2 COST ANALYSIS

The information obtained from the surveys and the interviews conducted with the transit systems, material suppliers, equipment suppliers, and the data developed by SEPTA during the test program were analyzed by life-cycle cost techniques to determine the total costs associated with resilient wheels, ring-damped wheels, wheel truing and rail grinding. The total costs for each technique of noise reduction are comprised of initial costs, maintenance costs and replacement costs, and are dependent upon the service life of material and equipment and maintenance and inspection cycles.

6.2.1 Wheels

As shown in the Initial Test Series Report, the purchase cost per wheel varies considerably (1977$), with solid steel wheels being the least expensive at $425 per wheel, followed by the Bochum wheel at $823.50, the Acousta Flex wheel at $990, and the SAB wheel at $1,225. Ring-damped wheels cost approximately $90 ($80 for groove, $10 for ring) more than solid steel wheels. Each of the resilient wheels is constructed to allow the replacement of the tire, thereby reducing replacement costs considerably when compared to the solid steel wheel or ring-damped wheel which must be replaced in its entirety when the tire reaches its condemning limit.

Tire life for the solid steel, Acousta Flex, and SAB wheels is similar according to the manufacturers' literature; however, the manufacturer of Bochum wheels claims -that the Bochum tire averages a 40-percent longer tire life than that achieved by solid steel wheels. Ring-damped wheels with the groove on the field side will have a tire life approximately 25% less than solid steel wheels because the groove reduces the effective thickness of the wheel tread by approximately 25%. The life of flange side, ring-damped wheels will be the same as solid steel wheels. Wheel and tire lives have a great effect on economic evaluations as present value calculations use life cycles as a basic input.

One of the goals of the testing program was to determine the service life of the various types of wheels by measuring the size of the wheels at various intervals throughout the service testing period and by keeping accurate records of mileage traveled by the test vehicles. Unfortunately, all resilient wheels were removed from the test cars prior to the accrual of sufficient mileage to allow a computation of expected tire life to be made.

Other factors contributing to the life-cycle cost of the wheels are the costs related to replacement and routine inspection. Concerning replacement, the manufacturers' estimate of the effort required to replace tires was far below the effort estimated by SEPTA, varying by as much as 92 man hours per car set in the case of Acousta Flex wheels. SEPTA's estimates were based upon very limited experience with resilient wheels and could have been influenced by their shop personnel's lack of confidence in the wheels. On the other hand, the manufacturers' figures are probably based upon optimized situations.

Similarly, SEPTA's wheel inspection cost estimates were also considerably above those of the manufacturers.

The sensitivity of these variances were determined by applying the various values to the life-cycle cost equations and examining the answers calculated. The life-cycle cost equations for resilient and solid steel wheels are as follows:

Equation 1 - Resilient Wheels

$$PV = \sum_{t=1}^{t=n+1,2n+1,\ldots\leq p} \frac{x_1 (1=i_f)^{t-1}}{(1+i)^{t-1}} + \sum_{L=m+1}^{L=2m+1,3m+1,\ldots\leq n} \frac{x_3 (1+i_f)^{L+t-2}}{(1+i)^{L=t-2}} - \sum_{L=m}^{L=2m,3m,\ldots\leq n} \frac{x_4 (1+i_f)^{L+t-1}}{(1+i)^{L+t-1}}$$

$$+ \sum_{t=1}^{t=p} \frac{x_2 (1+i_f)^{t}}{(1+i)^{t}} - \sum_{t=n}^{t=2n,3n,\ldots\leq p} \frac{x_5 (1+i_f)^{t}}{(1+i)^{t}} - \frac{\left[\frac{0.75x_1 - x_5}{n-1}\right](a-p)(1+i_f)^p}{(1+i)^p}$$

$$\frac{\left[\frac{0.75x_3 - x_4}{m-1}\right]\left[b-(p-(a-n))\right](1+i_f)^p}{(1+i)^p}$$

Where:

PV = present value of life cycle costs (\$)

X_1^* = initial cost of resilient wheels (\$)

X_2 = annual cost of inspecting resilient wheels (\$)

X_3^{**} = cost of replacing portions of the resilient wheels (tires, inserts, etc.) (\$)

X_4 = scrap value of replaced parts (\$)

X_5 = scrap value of complete wheel at end of service life (\$)

n = service life of wheel (years)

i = annual interest rate (decimal equivalent)

i_f = annual inflation rate (decimal equivalent)

m = service life of replacement parts (tires, inserts, etc) (years)

a = a multiple of n just greater than or equal to p (i.e., $a=k_1 n \quad p \quad (k_1-1)n$, k_1 being an integer)

b = a multiple os m just greater than or equal to p-(a-n) (i.e., $b=k_2 m \geq p-(a-n) > (k_2-1)m$, k_2 being an integer)

P = total years in period under consideration

---

* Initial cost includes purchase price + cost of installation + cost of any special equipment required for installation of resilient wheels

** Replacement costs include purchase price + cost of installation

Equation 2 - Solid Steel Wheels

$$PV = \sum_{t=1}^{\substack{t=n+1,2n+1,\\ \cdots \leq p}} \frac{x_6(1+i_f)^{t-1}}{(1+i)^{t-1}} + \sum_{t=1}^{t=p} \frac{x_7(1+i_f)^t}{(1+i)^t} - \sum_{t=n}^{\substack{t=2n,3n,\\ \cdots \leq p}} \frac{x_8(1+i_f)^t}{(1+i)^t}$$

$$\frac{\left[\dfrac{0.75x_6-x_8}{n-1}\right](a-p)(1+i_f)^p}{(1+i)^p}$$

Where:

X_6^* = initial cost of solid steel wheels ($)

X_7 = annual cost of inspecting solid steel wheels ($)

X_8 = scrap value of wheel at end of service life ($)

* Initial cost includes purchase price + cost of installation

Using the above equations and the data contained in the Initial Test Series Report, the difference between the present value of the life-cycle costs, using SEPTA installation and maintenance estimates as compared to the manufacturers installation and maintenance estimates, was calculated to be 4.3 percent. From this it was deduced that the life-cycle costs for resilient wheels are not sensitive to the variations in estimates of the effort required to inspect and maintain the wheels, but are dependent only upon initial costs and the length of service life.

6.2.2 Wheel Truing

Wheel truing is a process whereby the original profile of a wheel is restored by cutting away a portion of the surface metal of a worn wheel in the area where the wheel contacts the rail. Wheel truing eliminates the additional noise caused by flat spots and other irregularities which may develop; improves ride quality under circumstances where large irregularities have developed, and reduces impact forces on the rail (thereby reducing track degradation) and extending wheel life. Wheel truing is also used to maintain proper wheel flange depth in order that fouling of turnouts and frogs will not occur.

Wheel truing can be performed on above floor or underfloor lathes, or on underfloor milling machines. In general, above floor lathes require wheels to be removed from the trucks and axles, whereas underfloor lathes and milling machines allow the truing operation to be performed with the wheels remaining in place on the vehicle. Because of the variance in the level of effort required, the cost of truing wheels varies greatly from system to system. For example, SEPTA expends $775 in labor costs to true a car set of wheels on an above floor lathe on their Broad Street line and only $85 to true a car set of wheels on an underfloor milling machine on the Market-Frankford line. The labor cost for truing wheels ranges from $300 to $850 per car set on above floor lathes, and from $85 to $160 per car set on underfloor equipment at the various transit systems in North America.

Since the cost of above floor and underfloor wheel truing equipment is similar, it is obvious that it is more economical to perform wheel truing operations on underfloor equipment provided that the shop facilities are designed to allow this operation.

The calculation of the present value of wheel truing life-cycle costs and the comparison of these costs for the various transit properties is of little value for the following reasons:

- In a number of cases, equipment was purchased many years ago, often in used condition, and as such the initial costs are not comparable.
- The annual cost of wheel truing is dependent upon the number of vehicles in the fleet.
- The service life of wheel truing equipment is unknown and could vary depending upon usage.

It is essential, however, that each rapid transit system have the capability to perform wheel truing in order to insure that wheels developing large flat spots or other major irregularities can be returned to normal, and to maintain proper wheel flange size. Therefore, the question whether or not wheel truing should be performed does not arise. However, depending on a system's wheel truing capacity, a more stringent criteria for when to true can be set.

6.2.3 Rail Grinding

Rail grinding is a process by which a rail mounted vehicle, outfitted with grinding stones, travels along the track removing a certain amount of metal from the surface of the rail, ultimately returning the surface of the rail to its original contour. The purpose of rail grinding is to eliminate the additional noise caused by rail irregularities such as corrugations; to increase surface contact between the wheels and rail. This provides an improved medium for signal transmission; and increases rail and wheel life by reducing contact stresses.

Rail grinding trains can be purchased or rented, the decision apparently based upon the incidence of track corrugations and the number of track miles that require grinding. Several systems such as GCRTA, MBTA and PATH do not employ rail grinding. Others such as BART, CTA, NYCTA and SEPTA have their own rail grinding equipment. PATCO contracts for rail grinding on a bi-yearly basis.

The calculation of the present value of rail grinding life-cycle costs and the comparison of these costs for the various transit properties is of little value because of the variance in the employment of rail grinding by the different properties and for reasons similar to those stated above for wheel truing.

7. REFERENCES

1. Michael C. Holowaty, Hugh J. Saurenman and Stanley M. Rosen, "In-Service Performance and Costs of Methods for Control of Urban Rail System Noise - Experimental Design," prepared for U. S. DOT, Report No. UMTA-MA-06-0025-76-4, May 1976.

2. Hugh J. Saurenman and Michael C. Holowaty, "In-Service Performance and Costs of Methods to Control Urban Rail System Noise - Test and Evaluation Plan" prepared for U. S. DOT, Report No. UMTA-MA-06-0025-76-4, January 1977.

3. Robert L. Shipley and Hugh J. Saurenman, "In-Service Performance and Costs of Methods to Control Urban Rail System Noise - Initial Test Series Report", prepared for U. S. DOT, Report No. UMTA-MA-06-0025-78-7, August 1978.

4. Hugh J. Saurenman, "In-Service Performance and Costs of Methods to Control Urban Rail System Noise - Second Test Series Report", prepared for U. S. DOT, Report No. UMTA-MA-06-0099-79-4, October 1979.

5. F. G. Rutty, "Resilient Wheels - Experience of London Transport," London Transport Report No. 8/74-C239 (Revised September 13, 1974).

6. Paul J. Remington, Michael J. Rudd and Istavan L. Ver, "Wheel/Rail Noise Generation," prepared for U. S. DOT, Report No. UMTA-MA-06-0025-75-10, May 1975.

7. George Paul Wilson, "BARTD Prototype Car 107 Noise Tests With Standard, Damped and Resilient Wheels: Ballast and Tie Tangent Track and Short Radius Subway Curves," Wilson, Ihrig & Associates, Final Report, June 21, 1972.

8. George Paul Wilson, "Transit Car Noise Levels Observed During Visits to Camden, Pittsburgh and Toronto," Wilson, Ihrig & Associates Letter Report to Parsons Brinckerhoff-Tudor-Bechtel of May 29, 1969.

9. George Paul Wilson, "Noise Levels from Operations of CTA Rail Transit Trains," Wilson, Ihrig & Associates Report May 1977.

10. S. Kosak, W. Dixon, W. Dunton and E. Schagrin, "Qualification Test Report - 2400 Series Rapid Transit Motor Cars, Chicago Transit Authority," Boeing Vertol Company, Report Number D335-10020-1, February 1977.

11. Armin T. Wright, "Evaluation of WMATA Transit Vehicle Acoustics and Potential for Improvement," Wilson, Ihrig & Associates Report, November 1975.

12. George Paul Wilson, "BARTD Car Noise Tests in Tunnels," Letter Report to Parsons Brinckerhoff-Tudor-Bechtel of November 29, 1972.

13. Erich K. Bender and Manfred Heckl, "Noise Generated by Subways Aboveground and in Stations," Bolt Beranek and Newman, Inc., Report No. OST-ONA-70-1, January 1970.

14. Unpublished data taken by Wilson, Ihrig & Associates, Inc., at WMATA Metro dated June 1978.

15. S. Slutsky, W. R. McShane and J. J. Storace, "Noise Degradation Over Time in Rail Rapid Transit Cars," Polytechnic Institute of New York for U.S. DOT, UMTA Report No. NY-11-0002-01, December 1978.

16. London Transport, Office of the Scientific Advisor. Investigations into Noise on Railways (Laboratory Investigation No. 128/X215). "Report On: The Effectiveness of Noise Damping Rings on Train Wheels." (September 30, 1974).

17. Boeing Vertol Interoffice Memorandum, "CTA Ring Damped Wheel Noise Test Report," dated May 19, 1975.

18. Steven L. Wolfe, "Noise and Vibration Test Report - 2400 Series Rapid Transit Cars," Wilson, Ihrig & Associates, Final Report, June 1977.

19. L. Strasberg and J. Tiessinga, "Vibration Properties of Two Ring Damped TTC Railway Wheels," Transit Systems R/D Research and Development Division, Ontario Ministry of Transportation & Communications, October 1978.

20. Paul J. Remington and Larry E. Wittig, "Second Workshop on Railway and Tracked Transit System Noise - Session V: Vehicle Interior Noise: Sources; Comfort Retrofit Noise Control of Rapid Transit Cars," Bolt Beranek and Newman, Inc., 1978 (approximate date).

21. Toronto Transit Commission, "Yonge Subway Northern Extension Noise and Vibration Study," Report RD 115/3, Technical Reports-Consultants, October 1976.

22. S. T. Lawrence, "Toronto's Double Tie Trackbed System," Toronto Transit Commission, Paper given at the American Public Transit Association Rapid Transit Conference, Chicago, June 5-8, 1978.

23. Unpublished data taken by Wilson, Ihrig & Associates, Inc., at WMATA Metro dated June 1977.

24. Unpublished data taken by Wilson, Ihrig & Associates, Inc. at MARTA dated September 1978.

25. George Paul Wilson, "Diabo Test Track Noise and Vibration Measurements," Wilson, Ihrig & Associates Technical Report June 1967.

26. Steven L. Wolfe, "Ground-Borne Vibration from 2000, 2200, and 2400 Series CTA Transit Trains," Wilson, Ihrig & Associates Preliminary Report October 1978.

27. A. D. Hunt, "Development of Subway Car Flat Wheel Monitoring System," Toronto Transit Commission Subway Construction Branch Engineering Department, Technical Reports, 1975.

APPENDIX A

GRAPHS OF AVERAGE SOUND LEVELS AND TABULATIONS OF MEASURED NOISE REDUCTIONS

The information presented in this Appendix is basically a summary of the results of the tests on the SEPTA system. In order to simplify the presentation of material in the main body of the report, most of the numerical results have been separated into the Appendix. Figures A-1 through A-7 present the overall average A-weighted sound levels for each test condition at SEPTA. In some cases, the levels shown are the average of several independent tests with the same wheel and rail wear condition; however, in all cases the Test Series 1 and 2 data have been presented separately. For more detailed information on the measurement results, refer to Interim Reports #3 and #4.

Note that the sound levels presented for the tangent track tests in Figures A-1 through A-5 are the average "normalized" levels. Before averaging, all of the test data were normalized to 60 km/hr assuming a speed dependence of 30 *log* V.

The average changes in sound level observed with the four noise control methods are tabulated in Tables A-1 through A-11. Note that the differences are given to the nearest tenth decibel. This should not be interpreted as indicating measurement or statistical accuracy of ±0.1 dB. The purpose is to show those differences which are found after averaging the data. The maximum accuracy of the instrumentation calibration is ±0.25 dB. For the tangent track data, the minimum difference for 95% confidence that the difference is real (e.g., that the

difference is not the result of normal random fluctuation of sound level) is 1.0 to 1.5 dBA.

Another factor that should be noted is that in Table A-4, comparing the wheel squeal levels before and after rail grinding, the levels from Test Series 1 and 2 have been combined, with the exception that the worn rail data from Test Series 1 has not been included in the averages. This was done because, after rail grinding in Test Series 1, the wheel squeal levels increased, and in Test Series 2 after rail grinding, the wheel squeal levels decreased. The before/after tests of Test Series 2 were done with better controlled conditions and, therefore, the worn rail data from Test Series 2 only has been used in Table A-4. Even though Table A-4 indicates a consistent reduction of wheel squeal level after rail grinding, because of the variable results from the two test series, and from other similar tests, it is not possible to conclude that rail grinding will consistently reduce wheel squeal levels.

In the testing, a total of seven test trains with wheels of different types or conditions were used. The test trains and the manner in which they are referred to in the Tables and Figures are listed below:

WORN STANDARD [Cars 613/623]: a 2-car train with standard wheels having approximately one year of wear at the start of the test program.

NEW STANDARD [Cars 755/756]: a 2-car married pair train with new standard wheels at the start of the test program.

GROOVED #1 [Cars 607/644]: a 2-car train with standard wheels grooved on the field side for ring-dampers. The wheels were new at the start of the Phase IV testing.

GROOVED #2 [Car 606]: a single car with standard wheels grooved on the field and flange sides. This car was used in the Phase VII tests only with the wheels in new condition.

ACOUSTA FLEX [Cars 628/645]: a 2-car train with new Acousta Flex resilient wheels. The wheels were removed from the test program before they received significant wear.

PENN BOCHUM [Cars 626/631]: a 2-car train with new Penn Bochum resilient wheels. The wheels were removed from the test program after approximately two months of revenue service.

SAB [Cars 609/630]: a 2-car train with new SAB resilient wheels. The wheels had approximately nine months of revenue service when they were removed from the test program.

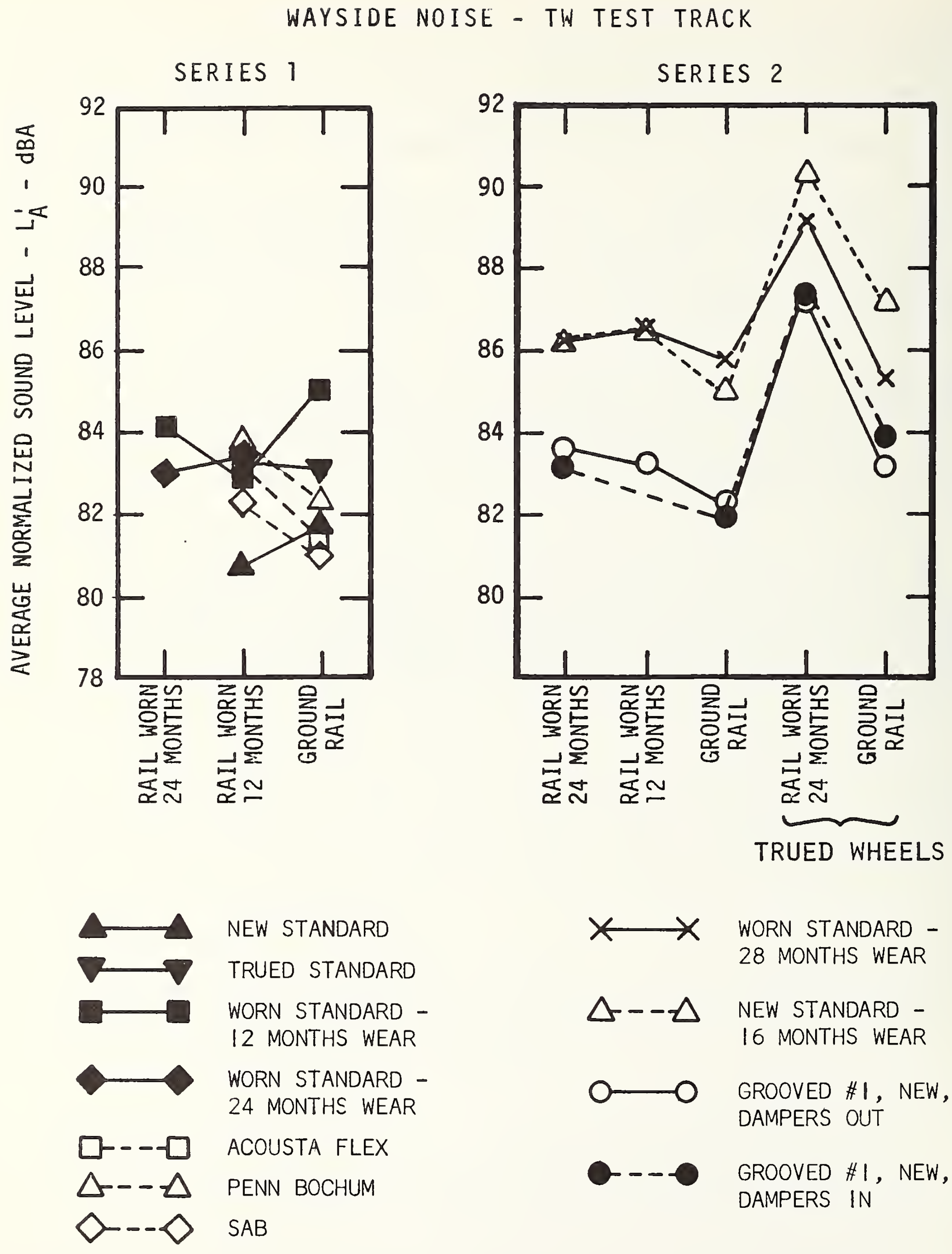


FIGURE A-1. AVERAGE WAYSIDE NOISE LEVELS AT TW TEST TRACK DURING SERIES 1 AND 2 FOR VARIOUS WHEELS AND RAIL CONDITIONS

LEVELS NORMALIZED TO TRAIN SPEED OF 60 km/hr

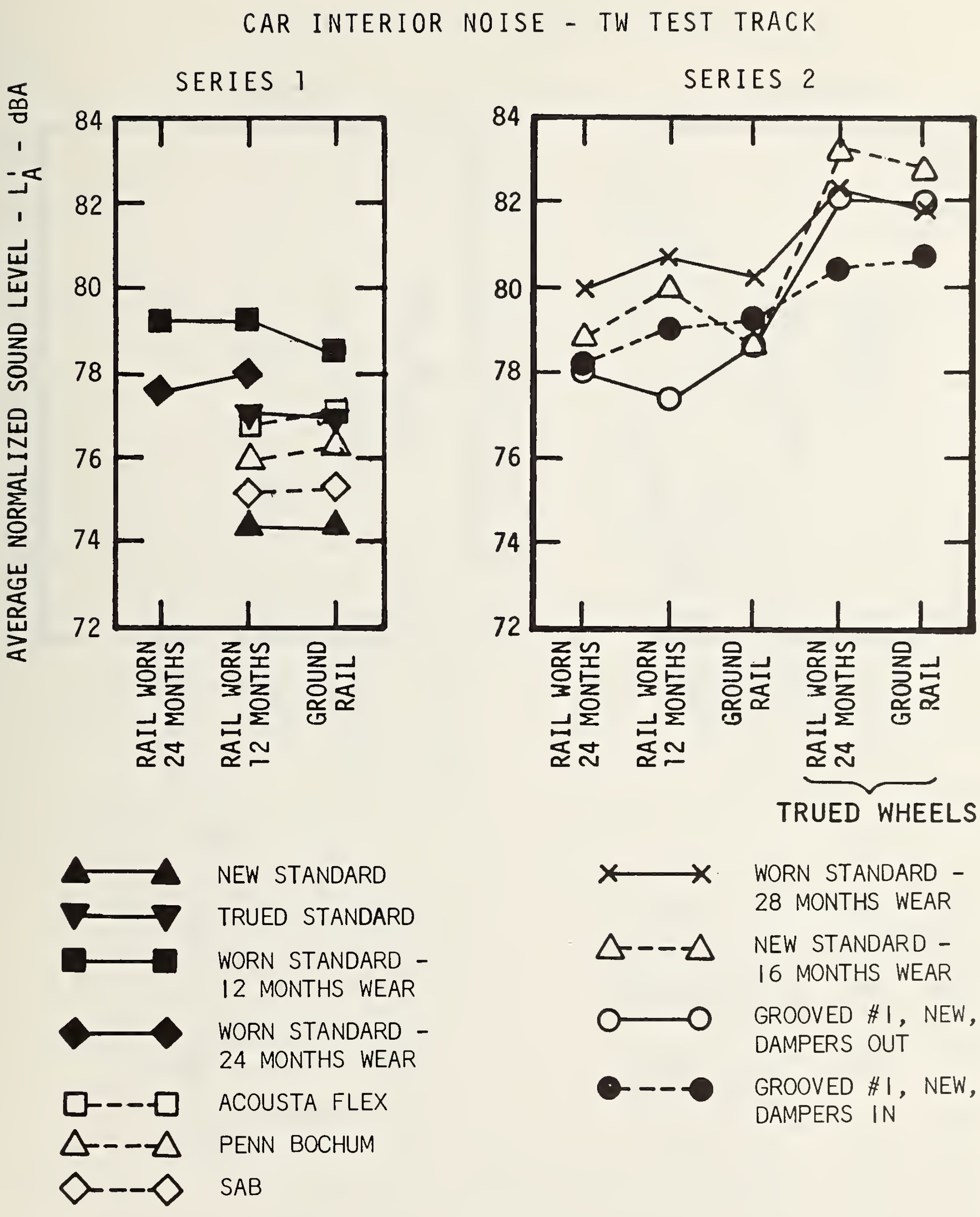


FIGURE A-2. AVERAGE CAR INTERIOR NOISE LEVELS AT TW TEST TRACK DURING SERIES 1 AND 2 FOR VARIOUS WHEELS AND RAIL CONDITIONS

LEVELS NORMALIZED TO TRAIN SPEED OF 60 km/hr

WAYSIDE NOISE - TJ TEST TRACK

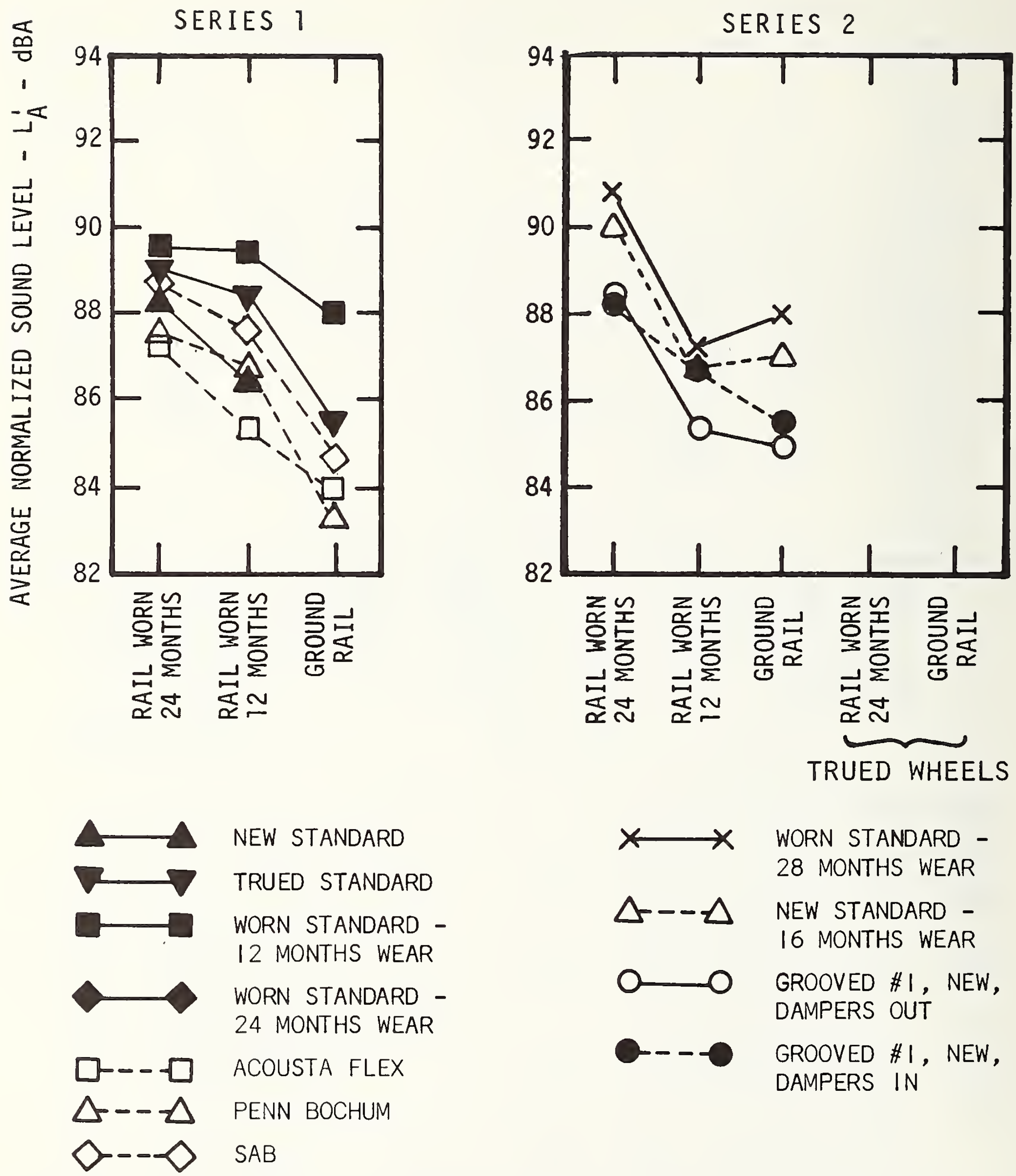


FIGURE A-3. AVERAGE WAYSIDE NOISE LEVELS AT TJ TEST TRACK DURING SERIES 1 AND 2 FOR VARIOUS WHEELS AND RAIL CONDITIONS

LEVELS NORMALIZED TO TRAIN SPEED OF 60 km/hr

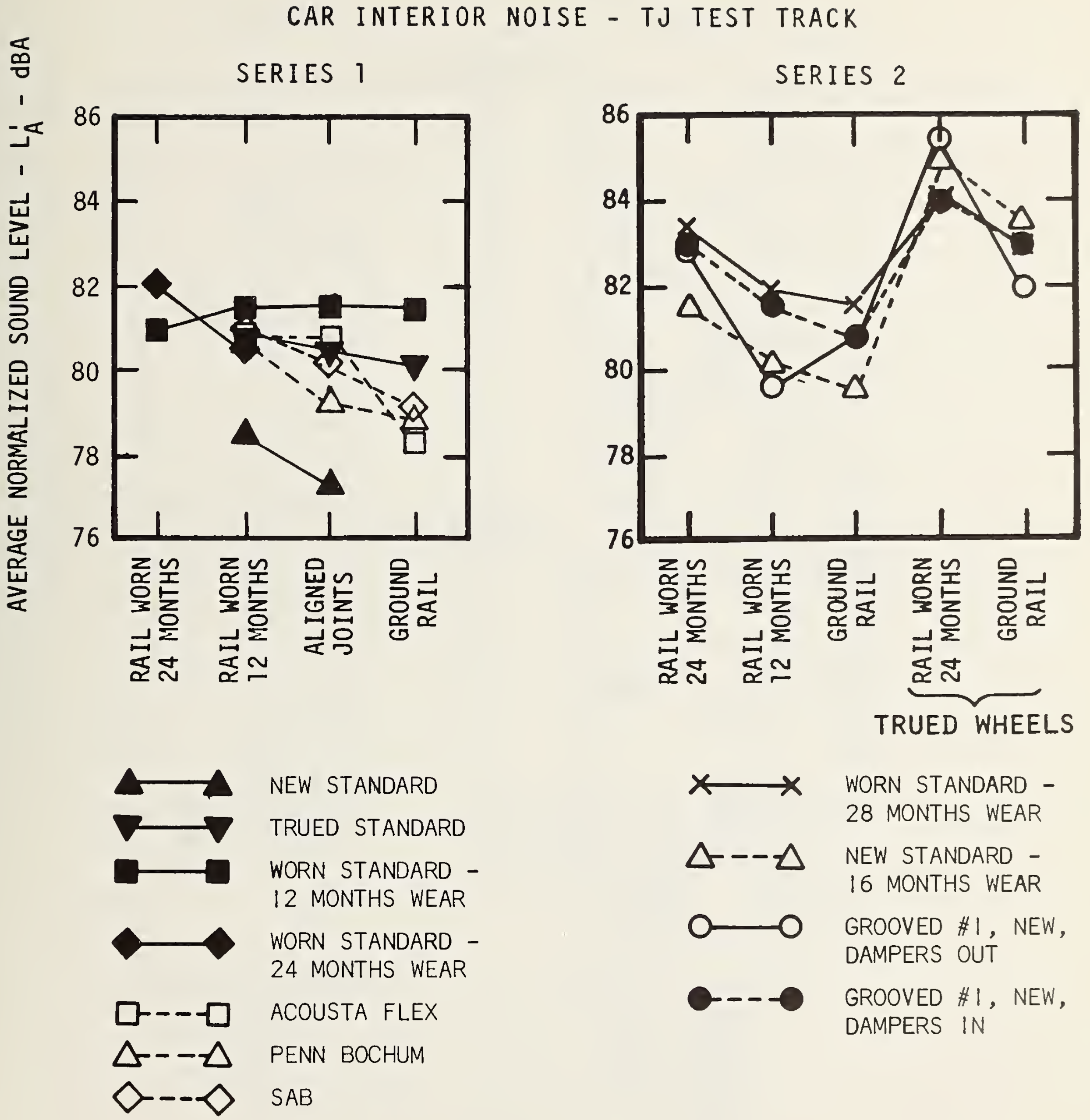


FIGURE A-4. AVERAGE CAR INTERIOR NOISE LEVELS AT TJ TEST TRACK DURING SERIES 1 AND 2 FOR VARIOUS WHEELS AND RAIL CONDITIONS

LEVELS NORMALIZED TO TRAIN SPEED OF 60 km/hr

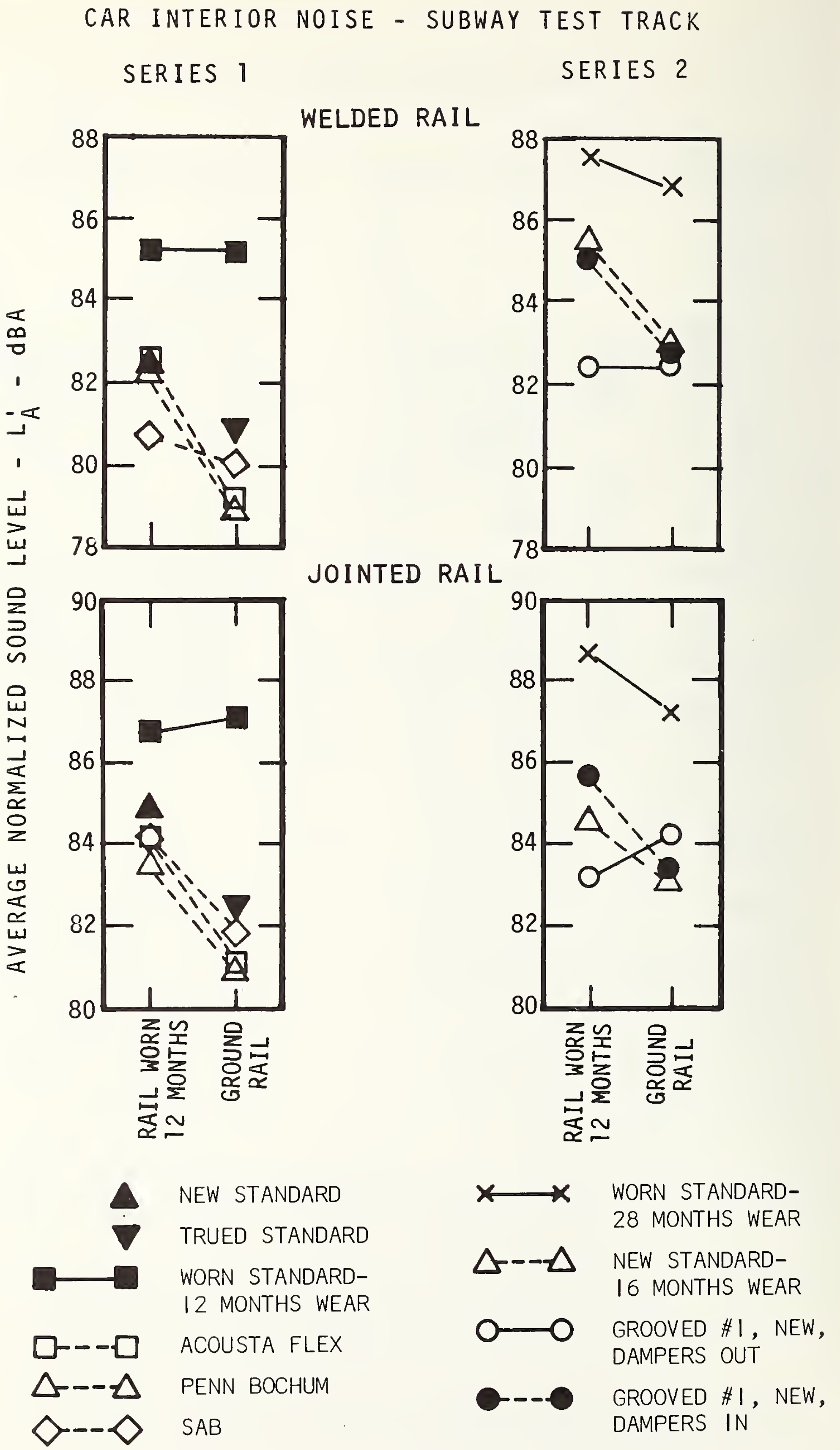


FIGURE A-5. AVERAGE CAR INTERIOR NOISE LEVELS AT SUBWAY TEST TRACKS DURING SERIES 1 AND 2 FOR VARIOUS WHEELS AND RAIL CONDITIONS

LEVELS NORMALIZED TO TRAIN SPEED OF 60 km/hr

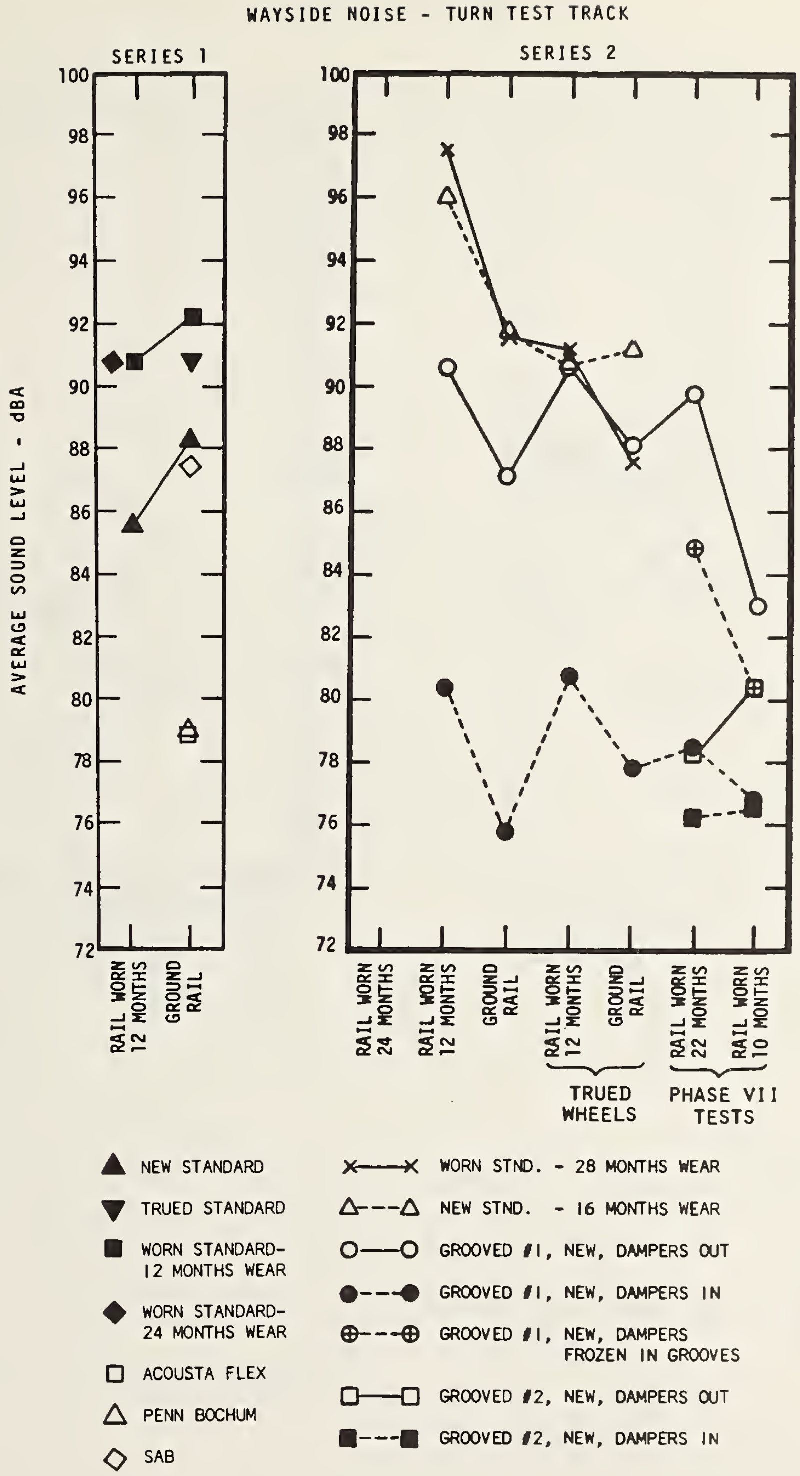


FIGURE A-6. AVERAGE WAYSIDE NOISE LEVELS AT TURN TEST TRACK DURING SERIES 1 AND 2 FOR VARIOUS WHEELS AND RAIL CONFIGURATIONS

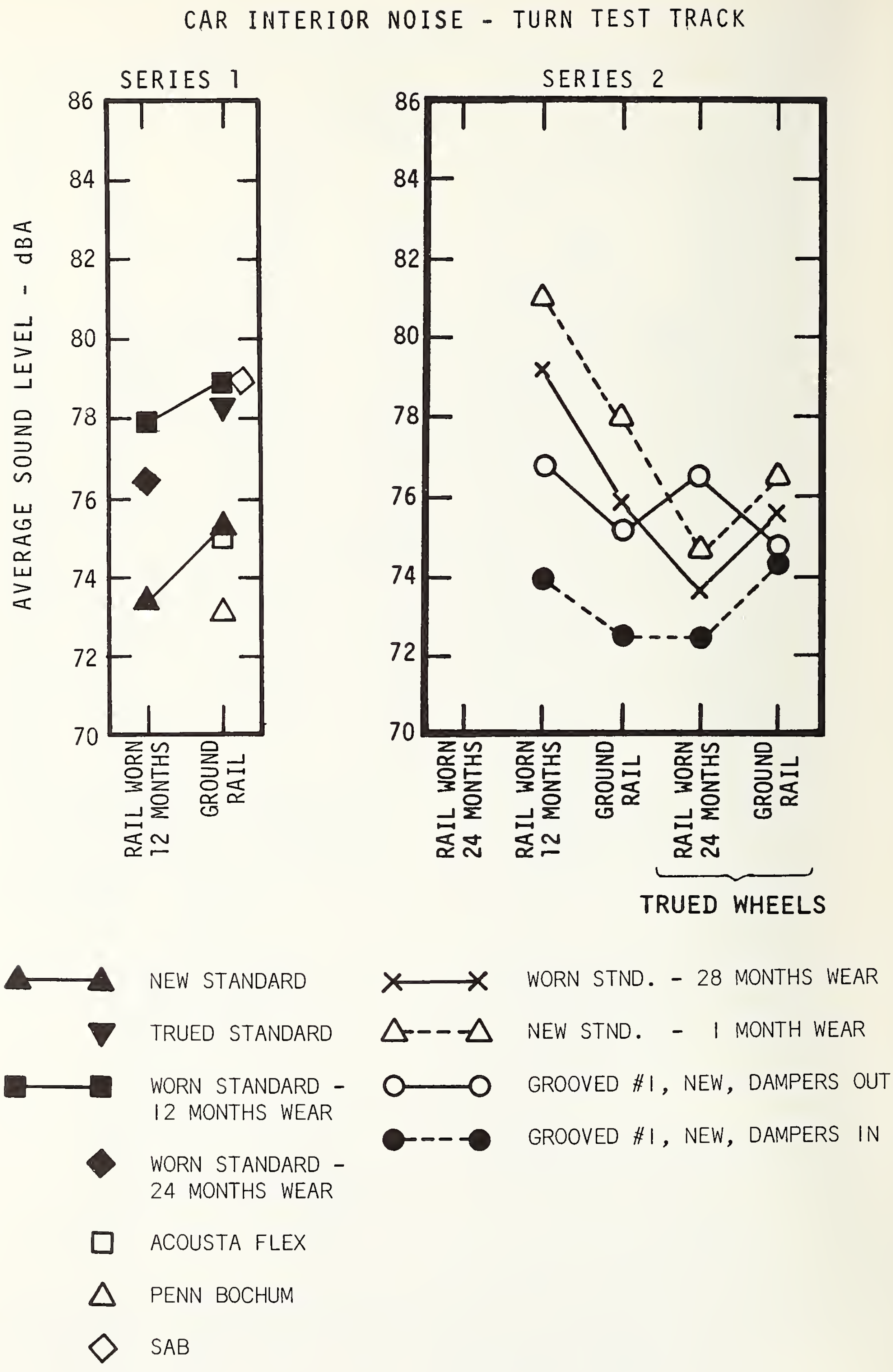


FIGURE A-7. AVERAGE CAR INTERIOR NOISE LEVELS AT TURN TEST TRACK DURING SERIES 1 AND 2 FOR VARIOUS WHEELS AND RAIL CONDITIONS

TABLE A-1. CHANGE IN NOISE LEVEL AFTER RAIL GRINDING ON TW TEST TRACK. FOR EACH WHEEL TYPE THE TABLE SHOWS LEVELS WITH GROUND RAILS AND RAILS WORN 24 MONTHS RELATIVE TO LEVELS WITH RAILS WORN BY 12 MONTHS OF NORMAL REVENUE SERVICE.

Train	Wheel Condition	Relative Level - dBA			
		Wayside		Car Interior	
		Rail Worn 24 Mo.	Rail Ground	Rail Worn 24 Mo.	Rail Ground
TEST SERIES 1					
<u>Standard Wheels</u>					
New Stnd.	New	--	+1.1	--	+0.2
New Stnd.	Trued	--	-0.2	--	0.0
Worn & New Stnd.	Worn, 12 Mo.	+0.9	+2.0	0.0	-0.7
Worn Stnd.	Worn, 24 Mo.	-0.4	--	-0.5	--
<u>Resilient Wheels</u>					
Acousta Flex	New	--	-2.0	--	+0.2
Penn Bochum	New	--	-1.4	--	+0.3
SAB	New	--	-1.1	--	+0.3
TEST SERIES 2					
<u>Standard Wheels</u>					
Grooved #1	New	+0.3	-1.1	+0.6	+2.2
New Stnd.	Worn, 16 Mo.	+0.2	-1.0	-1.1	-1.4
Worn Stnd.	Worn, 28 Mo.	-0.3	-0.1	-0.8	-0.5
Grooved #1, New & Worn Stnd.	Trued	--	-3.7*	--	-0.3*
<u>Ring-Damped Wheels</u>					
Grooved #1	New	--	-1.2*	+0.8	+0.2
Grooved #1	Trued	--	-3.6*	--	-0.3*

*Levels relative to rail worn by 24 months of revenue service.

TABLE A-2. CHANGE IN NOISE LEVEL AFTER RAIL GRINDING ON TJ TEST TRACK. FOR EACH WHEEL TYPE THE TABLE SHOWS THE LEVEL WITH GROUND RAILS AND RAILS WORN 24 MONTHS RELATIVE TO RAIL WORN BY 12 MONTHS OF NORMAL REVENUE SERVICE

Train	Wheel Condition	Relative Level - dBA			
		Wayside		Car Interior	
		Rail Worn 24 Mo.	Rail Ground	Rail Worn 24 Mo.	Rail Ground
TEST SERIES 1					
Standard Wheels					
New Stnd.	Trued	--	-3.1	--	-0.8
Worn Stnd.	Worn, 12 Mo.	--	-1.6	-0.6	-1.0
Worn Stnd.	Worn, 24 Mo.	--	--	+1.6	--
Resilient Wheels					
Acousta Flex	New	--	-3.4	--	-2.3
Penn Bochum	New	--	-3.0	--	-1.6
SAB	New	--	-3.8	--	-1.8
TEST SERIES 2					
Standard Wheels					
Grooved #1	New	+3.0	-0.4	+3.4	+1.2
New Stnd.	Worn, 12 Mo.	+3.2	+0.3	+1.3	-0.6
Worn Stnd.	Worn, 28 Mo.	+3.6	+0.8	+1.5	-0.4
Grooved #1, New & Worn Stnd.	Trued	--	--	--	-2.0*
Ring-Damped					
Grooved #1	New	+1.5	+0.3	+1.4	-1.0
Grooved #1	Trued	--	--	--	-1.0*

*Levels relative to rails worn 12 months.

TABLE A-3. CHANGE IN CAR INTERIOR NOISE LEVEL AFTER RAIL GRINDING SUBWAY TEST TRACKS. THE TABLE SHOWS THE LEVELS WITH GROUND RAILS RELATIVE TO LEVELS WITH RAIL WORN BY 12 MONTHS OF NORMAL REVENUE SERVICE

Train	Wheel Condition	Relative Level - dBA	
		Welded Rail	Jointed Rail
TEST SERIES 1			
Standard Wheels			
New Stnd.	New/Trued*	-1.5	-2.5
Worn Stnd.	Worn, 12 Mo.	-0.1	+0.6
Resilient Wheels			
Acousta Flex	New	-3.2	-2.8
Penn Bochum	New	-2.9	-2.8
SAB	New	-0.8	-2.2
TEST SERIES 2			
Standard Wheels			
Grooved #1	New	+0.1	+1.0
New Stnd.	Worn, 12 Mo.	-2.4	-1.5
Worn Stnd.	Worn, 24 Mo.	-0.5	-1.4
Ring-Damped Wheels			
Grooved #1	New	+2.3	-2.5

*Train tested with wheels in new condition on worn rail. The ground rail tests were not performed until after the wheels had been trued.

TABLE A-4. CHANGE IN WHEEL SQUEAL NOISE LEVELS AFTER GRINDING TURN TEST TRACK. THE TABLE SHOWS, FOR EACH COMBINATION OF WHEEL TYPE, THE AVERAGE LEVELS WITH GROUND RAILS RELATIVE TO THE AVERAGE LEVELS FOR THE TEST SERIES 2 WORN RAILS. THE GROUND RAIL RESULTS FROM TEST SERIES 1 AND TEST SERIES 2 HAVE BEEN COMBINED FOR THIS TABLE.

Wheel Type	Wheel Condition	Relative Level - dBA	
		Wayside	Car Interior
Standard	New	-3.0	-2.6
Standard	Trued	-1.4	+1.0
Standard	Worn, ∿1 yr.	-4.0	-2.6
Standard	Worn, ∿2 yrs.	-5.9	-2.7
Ring-Damped*	New	-1.9	-1.4
Ring-Damped*	Trued	-3.0	+1.9

*Ring-dampers installed

TABLE A-5. EFFECTIVENESS OF WHEEL TRUING AT REDUCING NOISE FOR TW TEST TRACK. THE NOISF LEVELS FOR STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO STANDARD WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED.

Train	Wheel Condition	Relative Noise Level - dBA					
		Wayside			Car Interior		
		Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground	Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground
TEST SERIES 1							
New Stnd.	New	--	-2.5	-3.4	--	-5.1	-4.2
New Stnd.	Trued	--	+0.4	-1.8	--	-2.2	-1.5
Worn Stnd.	Worn, 24 Mo.	-0.9	+0.4	--	-1.6	-1.1	--
TEST SERIES 2							
Grooved #1	New	-2.6	-3.1	-2.8	-0.9	-2.6	+1.0
Grooved #1, New & Worn Stnd.	Trued	+2.7	--	-0.5	+3.7	--	+3.6
Worn Stnd.	Worn, 28 Mo.	0	+0.1	+0.8	+1.0	+0.7	+1.6

TABLE A-6. EFFECTIVENESS OF WHEEL TRUING AT REDUCING NOISE FOR TJ TEST TRACK. THE NOISE LEVELS FOR STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO STANDARD WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED.

Train	Wheel Condition	Relative Noise Level - dBA					
		Wayside			Car Interior		
		Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground	Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground
TEST SERIES 1							
New Stnd.	New	--	-1.4	--	--	-3.1	--
New Stnd.	Trued	--	-0.9	-2.4	--	-0.6	-0.4
Worn Stnd.	Worn, 24 Mo.	--	--	--	+1.1	-1.1	--
TEST SERIES 2							
Grooved #1	New	-1.6	-1.4	-2.1	+1.5	-0.6	+1.2
Grooved #1, New & Worn Stnd.	Trued	--	--	--	+3.3	--	+3.2
Worn Stnd.	Worn, 28 Mo.	+0.8	+0.4	+0.9	+1.9	+1./	+1.9

TABLE A-7. EFFECTIVENESS OF WHEEL TRUING AT REDUCING CAR INTERIOR NOISE FOR SUBWAY TEST TRACKS. THE LEVELS FOR STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO STANDARD WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED.

Train	Wheel Condition	Relative Noise Level - dBA			
		Welded Rail		Jointed Rail	
		Worn 12 Mo.	Ground	Worn 12 Mo.	Ground
TEST SERIES 1					
New Stnd.	New	-2.8	--	-1.9	--
New Stnd.	Trued	--	-4.2	--	-4.8
TEST SERIES 2					
Grooved #1	New	-3.0	-0.5	-3.4	+0.1
Worn Stnd.	Worn, 28 Mo.	+2.0	+3.9	+2.1	+4.2

TABLE A-8. EFFECTIVENESS OF WHEEL TRUING AT REDUCING WHEEL SQUEAL. THE LEVELS WITH STANDARD WHEELS NEW, TRUED AND WORN RELATIVE TO WHEELS WITH APPROXIMATELY 1 YEAR OF WEAR ARE INDICATED. THE RESULTS OF TEST SERIES 1 AND TEST SERIES 2 HAVE BEEN COMBINED TO DERIVE THIS TABLE.

Wheel Condition	Relative Noise Level - dBA			
	Wayside		Car Interior	
	Rail Worn 12 Mo.	Rail Ground	Rail Worn 12 Mo.	Rail Ground
New - Lathe turned	-5.2	-4.4	-4.3	-3.2
Trued	-5.2	-2.6	-6.0	-2.4
Worn, 2 years	+0.8	-0.4	-2.0	-2.5

TABLE A-9. EFFECTIVENESS OF RESILIENT WHEELS AT REDUCING NOISE. THE TABLE SHOWS THE LEVELS WITH RESILIENT WHEELS RELATIVE TO LEVELS WITH TRUED STANDARD STEEL WHEELS FOR THE SEPTA TESTS.

Wheel Type	Relative Noise Level - dBA			
	Wayside		Car Interior	
	Rail Worn 12 Mo.	Rail Ground	Rail Worn 12 Mo.	Rail Ground
TW TEST TRACK				
Acousta Flex	-0.1	-1.9	-0.8	-0.6
Penn Bochum	+0.2	-1.0	-1.1	-0.8
SAB	-0.3	-0.6	-1.8	-1.5
TJ TEST TRACK				
Acousta Flex	-1.3	-1.6	0.0	-1.5
Penn Bochum	-1.1	-2.0	-0.3	-1.1
SAB	-0.1	-0.8	+0.1	-0.9
WELDED SUBWAY TRACK				
Acousta Flex	--	--	+0.1*	-1.6
Penn Bochum	--	--	-0.4*	-1.8
SAB	--	--	-1.6*	-0.9
JOINTED SUBWAY TRACK				
Acousta Flex	--	--	-0.7*	-1.0
Penn Bochum	--	--	-1.1*	-1.4
SAB	--	--	-0.7*	-0.4
TURN TRACK				
Acousta Flex	--	-9.3*	--	-1.3*
Penn Bochum	--	-8.4*	--	-1.9*
SAB	--	-3.8*	--	+1.2
FROG				
Acousta Flex	-1.0	--	--	+1.3
Penn Bochum	-0.9	--	--	+1.9
SAB	-0.8	--	--	-0.1

*Levels relative to new [lathe-turned] standard wheels.

TABLE A-10. REDUCTION OF SOUND LEVELS WITH RING-DAMPED WHEELS ON TANGENT TRACK. OVERALL SOUND LEVELS WITH RINGS IN RELATIVE TO RINGS OUT. ALL TESTS WERE WITH GROOVED #1 TRAIN.

Rail Condition	Relative Noise Level - dBA			
	Wayside		Car Interior	
	New Wheels	Trued Wheels	New Wheels	Trued Wheels
TW				
Ground	-0.2	+0.6	-0.4	-1.2
Worn, 12 Mo.	--	--	+1.6	--
Worn, 24 Mo.	-0.4	+0.1	+0.2	-1.6
AVG.	-0.3	+0.3	-0.6	-1.4
TJ				
Ground	+0.6	--	0.0	+1.1
Worn, 12 Mo.	+1.4	--	+2.2	--
Worn, 24 Mo.	-0.1	--	+0.2	-1.5
AVG.	+0.6	--	+1.2	-0.2
SUB 1 [Welded]				
Ground	--	--	+0.3	--
Worn, 12 Mo.	--	--	+2.7	--
AVG.	--	--	+1.5	--
SUB 2 [Jointed]				
Ground	--	--	-0.9	--
Worn, 12 Mo.	--	--	+2.6	--
AVG.	--	--	+0.8	--

TABLE A-11. AVERAGE EFFECTIVENESS OF RING-DAMPED WHEELS AT REDUCING WHEEL SQUEAL. OVERALL SOUND LEVELS WITH RINGS IN RELATIVE TO OVERALL SOUND LEVELS WITH RINGS OUT.

Train	Wheel Condition	Relative Noise Level - dBA					
		Wayside			Car Interior		
		Rail Worn	Rail Ground	AVG.	Rail Worn	Rail Ground	AVG.
Grooved #1	New	-10.2	-11.3	-10.8	-2.8	-2.5*	-2.6
Grooved #2	New	-2.1*	-4.6	-2.9	--	--	--
Grooved #1	Trued	-10.0	-10.3	-10.2	-2.4*	-1.2*	-1.8
Grooved #1	Worn[1]	-4.9	-2.6*	-3.8	--	--	--
Grooved #1	Worn[2]	-11.4	-6.2	-8.8	--	--	--
AVG.[3]	--	-10.5	-9.3	-9.9	-2.6	-1.8	-2.2

*Differences not statistically significant at 0.05 level.

[1] Phase VII Tests with Cars 607/644, rings frozen in place.

[2] Phase VII Tests with Cars 607/644, new rings installed.

[3] Average excludes tests with rings frozen in place and Grooved #2 tests.

APPENDIX B

REPORT OF NEW TECHNOLOGY

A detailed review of work performed under this contract and the material contained in this report has not disclosed any new technology. However, the work reported here represents improved engineering data on the costs and performance of four types of commercially available urban rail noise control techniques for which such data was previously inadequate. These techniques are resilient wheels, ring-damped wheels, wheel truing and rail grinding.